357SERBSF10,620

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U.S. ENVIRONMENTAL PROTECTION AGENCY,
REGION IV, WASTE MANAGEMENT DIVISION.

SOUTHERN WOOD PIEDMONT COMPANY - WILMINGTON SITE
NCD 058 517 467
EXPANDED SITE INSPECTION

REFERENCES
(16-21)
JULY 1997

BVSPC

Southern Wood Piedmont
52014255

Ben Meadows
1-800-241-6401
FIELD BOOK
#101595

FIELD BOOK Vol 2

II

12/15/96 to
1/29/97

Reference 16

Black and Veatch Special Projects Corp.

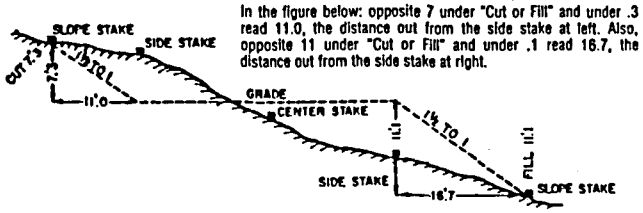
Southern Wood Piedmont
52014.755

Logbook 2 of 2

DISTANCES FROM SIDE STAKES FOR CROSS-SECTIONING

Roadway of any Width. Side Slopes 1½ to 1.

In the figure below: opposite 7 under "Cut or Fill" and under .3 read 11.0, the distance out from the side stake at left. Also, opposite 11 under "Cut or Fill" and under .1 read 16.7, the distance out from the side stake at right.



Cut or Fill	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	Cut or Fill
	Distance out from Side or Shoulder Stake										
0	0.0	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.2	1.4	0
1	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7	2.9	1
2	3.0	3.2	3.3	3.5	3.6	3.8	3.9	4.1	4.2	4.4	2
3	4.5	4.7	4.8	5.0	5.1	5.3	5.4	5.6	5.7	5.9	3
4	6.0	6.2	6.3	6.5	6.6	6.8	6.9	7.1	7.2	7.4	4
5	7.5	7.7	7.8	8.0	8.1	8.3	8.4	8.6	8.7	8.9	5
6	9.0	9.2	9.3	9.5	9.6	9.8	9.9	10.1	10.2	10.4	6
7	10.5	10.7	10.8	11.0	11.1	11.3	11.4	11.6	11.7	11.9	7
8	12.0	12.2	12.3	12.5	12.6	12.8	12.9	13.1	13.2	13.4	8
9	13.5	13.7	13.8	14.0	14.1	14.3	14.4	14.6	14.7	14.9	9
10	15.0	15.2	15.3	15.5	15.6	15.8	15.9	16.1	16.2	16.4	10
11	16.5	16.7	16.8	17.0	17.1	17.3	17.4	17.6	17.7	17.9	11
12	18.0	18.2	18.3	18.5	18.6	18.8	18.9	19.1	19.2	19.4	12
13	19.5	19.7	19.8	20.0	20.1	20.3	20.4	20.6	20.7	20.9	13
14	21.0	21.2	21.3	21.5	21.6	21.8	21.9	22.1	22.2	22.4	14
15	22.5	22.7	22.8	23.0	23.1	23.3	23.4	23.6	23.7	23.9	15
16	24.0	24.2	24.3	24.5	24.6	24.8	24.9	25.1	25.2	25.4	16
17	25.5	25.7	25.8	26.0	26.1	26.3	26.4	26.6	26.7	26.9	17
18	27.0	27.2	27.3	27.5	27.6	27.8	27.9	28.1	28.2	28.4	18
19	28.5	28.7	28.8	29.0	29.1	29.3	29.4	29.6	29.7	29.9	19
20	30.0	30.2	30.3	30.5	30.6	30.8	30.9	31.1	31.2	31.4	20
21	31.5	31.7	31.8	32.0	32.1	32.3	32.4	32.6	32.7	32.9	21
22	33.0	33.2	33.3	33.5	33.6	33.8	33.9	34.1	34.2	34.4	22
23	34.5	34.7	34.8	35.0	35.1	35.3	35.4	35.6	35.7	35.9	23
24	36.0	36.2	36.3	36.5	36.6	36.8	36.9	37.1	37.2	37.4	24
25	37.5	37.7	37.8	38.0	38.1	38.3	38.4	38.6	38.7	38.9	25
26	39.0	39.2	39.3	39.5	39.6	39.8	39.9	40.1	40.2	40.4	26
27	40.5	40.7	40.8	41.0	41.1	41.3	41.4	41.6	41.7	41.9	27
28	42.0	42.2	42.3	42.5	42.6	42.8	42.9	43.1	43.2	43.4	28
29	43.5	43.7	43.8	44.0	44.1	44.3	44.4	44.6	44.7	44.9	29
30	45.0	45.2	45.3	45.5	45.6	45.8	45.9	46.1	46.2	46.4	30
31	46.5	46.7	46.8	47.0	47.1	47.3	47.4	47.6	47.7	47.9	31
32	48.0	48.2	48.3	48.5	48.6	48.8	48.9	49.1	49.2	49.4	32
33	49.5	49.7	49.8	50.0	50.1	50.3	50.4	50.6	50.7	50.9	33
34	51.0	51.2	51.3	51.5	51.6	51.8	51.9	52.1	52.2	52.4	34
35	52.5	52.7	52.8	53.0	53.1	53.3	53.4	53.6	53.7	53.9	35
36	54.0	54.2	54.3	54.5	54.6	54.8	54.9	55.1	55.2	55.4	36
37	55.5	55.7	55.8	56.0	56.1	56.3	56.4	56.6	56.7	56.9	37
38	57.0	57.2	57.3	57.5	57.6	57.8	57.9	58.1	58.2	58.4	38
39	58.5	58.7	58.8	59.0	59.1	59.3	59.4	59.6	59.7	59.9	39
40	60.0	60.2	60.3	60.5	60.6	60.8	60.9	61.1	61.2	61.4	40

The paper in this book is made of 50% high grade rag stock with a WATER RESISTING surface sizing.

CONTENTS

PAGE NO.	REFERENCE	DATE
	(713) 519 1461 Carol Schatter	MO

Cut or Fill

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

12/15/96, Sunday ≈ 50°, Clear, windy ≈ 10mph

8:40. BVSPC personnel: Joe Sykerman, Carter Helm, and Frank Jewell arrive onsite + prepare for the days activities. Carter Helm will be recording in the main logbook (Vol. 1) Jewell will record sampling activities in this logbook Vol. 2.

800. Sykerman + Jewell arrive at MW40, MW41 + MW42 [Helm went to develop other well clusters.

915. Water level @ MW40 is 5.62 (Depth to Water) Total Well depth is 16.70, Thus well ~~column~~ column is 11.08 [x 0.17 = 1.88] ~~Bpw~~ 5.65 ~~and~~ ~~gallons~~ gals will be purged.

9:20 Depth to Water @ MW-41 is 5.08. (Intermediate Well). Total well depth is 40.14. Thus well column is 35.06 [(x 0.17) = 5.96] ≈ 18 gals will be purged

9:25 Depth to water @ MW-42 (Deep Well) is 4.90 Total well depth is 66.96. Well column is 62.06 (x 0.17 = 10.55) ≈ 32 gallons will be purged. Note water level indicator is deconned between measurements.

940 Began purging deep well (MW-42).

Time	Temp	pH	Cond.	Turb.
950	59.2°	7.22	477	6.0
955	61.4°	8.05	446	3.0
1010	60.6°	8.38	425	1.15
1015	61.3°	8.44	450	0.80

≈32 gallons purged from MW-42

Rex 1/27/97

(2) RLM 1/27/97

945 Begin purging shallow well MW40

Time	Temp	pH	Cond.	Turb
955	58.0	7.58	506	18
1015	60.2	7.79	522	30
1030	58.9	7.90	496	4.0
1045	58.4	7.85	545	2.0
1053	58.9	7.98	579	2.0

1320 - Begin collecting sample SP-MW-42. VOA collected first. All samples will be collected accd to procedures outlined in the field study plan.

1045. SP-MW-42 complete

1050. Jewell preserves metals + cyanide portion of sample. Metals preserved w/ HNO_3 and cyanide preserved w/ NaOH.

10:55 ≈ 52 gallons purged from MW-40. Begin collecting sample VOA collected first

1125. Sample SP-MW-40 complete. metals/cyn preserved.

1143. Begin purging MW-41

Time	Temp	pH	Cond	Turb
1140	62.5	7.91	345	4.0
1150	60.4	7.94	324	3.5
1200	60.5	7.92	335	5.2

≈ 25 gallons purged.

1205. Begin collecting SP-MW-41. VOA collected first.

(3) RLM 1/27/97

1225. Jewell preserves metals/cyanide portion of sample.

1235. Sample complete. Slykerman + Jewell load equipment in vehicle and depart location SP-MW-40/41+42 and go to meet Helm, who is developing wells at location SP-MW-31/32/33

Personnel decon submersible pumps.

1245. Arrive @ MW-31/32/33. Helm is still in the process of developing wells.

1300 Slykerman and Jewell depart for lunch. Helm remains outside to develop wells.

1415. Slykerman and Jewell return to site.

1435. Depth to water at Deep well MW33 is 2 ~~5.70~~ 7.60

Total well depth is 55.70. Well column is 53.10 (55.70 − 2.60 = 53.10), > 27.09 gallons will be purged.

Water Measurements for MW-33

Time	Temp.	pH	Cond.	Turbidity
1500	61.2	7.98	530	22.0
1510	58.6	8.49	559	11.6
1515	59.6	8.60	581	4.0
1525	58.1	8.66	573	4.0
1528	60.2	8.73	598	3.0

1450 Begin purging MW-33

Water has a petroleum odor

1530 ≈ 54 gallons purged from MW-33

(4)
RLM
1/27/97

1830 Begin collecting SP-MW-33. VOA collected first.
1845 Jewell Preserves metals/cyanide portion
1600 Sample Complete.
1615 Personnel decon submersible pumps
1620 Personnel collect Trip Blank + Preservative Blank.
C. Helm remains + develops wells.
1655 Personnel (Jewell + Slykerman) begin processing samples
1800 Slykerman + Jewell finish processing. End of day.

Jewell relisle

≈48° clear, light wind ≈ 4 miles per hr.

(5)
RLM
1/27/97

Monday, 12/16/96
8:15 Personnel arrive onsite. Mr. Philips from SWP arrives onsite and speaks to Helm.
830 Slykerman and Jewell set up at MW-31 and MW-32.
840. Depth to water at MW-31 is 4.70 ft. below ground surface. Total well depth is 6.22, thus well column is 1.52 (X 0.17 = 1.96) ≈ 6 gallons or more will be purged from MW-31.

Water Measurements for MW-31 (shallow well)

Time	Temp	pH	cond.	Turbidity
915	54.9	7.60	806	13.2
930	57.0	7.44	911	12.2
940	53.6	7.71	806	7.1
9:55	58.5	6.76	848	7.5
1005	58.6	7.78	824	1.2

≈ 8 gallons purged.
855 Slykerman leaves with Helm to start submersible pump for development.
900. Depth to water @ MW-32 is 3.92. Total well depth is 46.20, thus well column is 42.28 (X 0.17) ≈ 21.5 gallons or more will be purged from MW-32

Time	Temp	pH	cond.	Turbidity
950	57.6	8.22	525	127.6
955	60.8	7.06	434	19.0
1000	59.6	8.20	402	3.6
1015	56.3	8.12	378	0.2
1020	60.1	8.02	396	5.5

RZM
1/27/97

NOTE: OILY SHEEN OBSERVED ON TOP OF PURGE WATER FROM MW-31

1010 Begin collecting sample from shallow well MW-31. VOs collected first.

1025 Begin collecting intermediate well sample ~~at~~ MW-32. VOs collected first

1035. MW-31 sample complete. Jewell preserves metals/cyanide portion of MW-31.

1045. sample for MW-32 complete. Jewell preserves metals/cyanide portion.

1100 Personnel depart for staging area. Slykerman decons submersible pump. Helm having trouble with pumps. Slykerman goes to assist helm in developing. Personnel cannot sample any more today ~~until~~ wells which Helm develops will need time to equilibrate. Jewell remains at staging area, processes samples and waits for the drum delivery.

~~1245 Drums delivered.~~

1200 Drums delivered.

1215 Jewell leaves site to contact office

1245 Jewell continues to process samples / Bag Ice.

1410 Jewell leaves site to get vermiculite for packing samples.

RZM
1/27/97

Slykerman remains onsite to assist Helm.

1600. Jewell returns to site. Jewell packs & prepares samples for shipment.

1730 Personnel depart site for Fed Ex.

1800 Personnel leave samples with Fed Ex for shipment.

Randall Jewell
12/16/96

RZM 1/27/97

Tuesday, 12/17/96 Weather: Clear, ≈ 47°

715 Personnel depart Hotel for site.

730 Personnel arrive onsite.

745. Slykerman decons submersible pump used to develop wells, yesterday.

805. Slykerman & Jewell arrive at MW-34/35/36.

Depth to water at Shallow well SP-MW-34 is 7.14 bls

Total well depth is 16.71; Well column is 9.5

(X 0.17 = 1.62) ≈ 4.85 or more gallons will be purged.

810. Water level @ Intermediate well MW-35 is 4.28 bls

Total well depth is 38.16; Well column is 33.88

(X 0.17 = 5.64) ≈ 16.92 or more will be purged.

815 Water level at Deep well MW-36 is 5.18 bls.

Total well depth is 51.18; Well column is 46

(X 0.17 = 7.82) ≈ 23.46 or more gallons will be purged.

Water Measurements for MW-34 (Shallow)

Time	Temp	pH	cond.	Turbidity
850	62.3	6.20	1,245	64.0
900	61.8	6.29	815	64.2
915	64.2	6.50	739	41.8
925	64.7	6.49	792	+900
945	62.4	6.66	746	67.5
1015	67.3	6.50	708	~~[illegible]~~ 087
1025	69.1	6.58	732	68

845 Began purging MW-34.

RZM 1/27/97

Water Measurements for MW-36 (Deep well)

Time	Temp.	pH	cond.	Turbidity
845	58.4	6.79	509	57.3
905	61.9	7.05	403	2.3
910	62.5	7.36	372	1.3
920	63.8	7.28	395	0.96

≈ 440 gallons of water purged from MW-36

845 Began purging MW-36. (Note @ 830 Slykerman calibrated pH & cond. meter.

(Note: Drillers arrive onsite ≈ 815)

935 Begin to collect SP-MW-36. VOA's collected first.

950 MW-36 sample complete. Slykerman goes to staging area to decon submersible pump. Jewell processes samples.

1025 Begin purging Intermediate well MW-35

1030 Begin collecting SP-MW-34 (Shallow well)

100 Collected first

Water Measurements for MW-35 (Intermediate)

Time	Temp	pH	cond.	Turbidity
1040	67.4	6.95	424	30.4
1050	67.3	7.01	415	20.9
1100	66.8	7.04	395	15.1
1110	67.6	7.04	413	5.1
1115	67.3	7.04	399	4.6

(10) RZM 1/27/97

Note: Approximately 9 gallons purged from MW-34.

1055 Jewell preserves metals/cyanide portion of MW-34 sample (metals/cyanide portion of MW-36 preserved, earlier.)

1120 Begin sampling MW-35 (Intermediate) VOA collected first. ≈40 gallons purged from MW-35.

1135. Jewell preserves metals/cyanide portion of sample

1140. Sample complete

1145. Slykerman departs wells + goes staging area to decon submersible pump.

1205. Slykerman + Jewell arrive at MW 37/38/39. to assist C. Helm in developing. Helm is having problems w/ the submersible pump. It is malfunctioning.

1220. Slykerman assist Helm in developing. Jewell departs site to contact Carol Scheffer, ATSMO to inform her about yesterday's shipment. Carol was not in, Jewell left information on Scheffer's voice mail. Jewell picks up lunch for personnell.

1315. Jewell arrives at Optimist park location. Jewell + Slykerman assist Helm with well development.

1735. Personnel depart site

~~Brian A. Jewell 1/27/96~~

(11) RZM 1/27/97

Wednesday, December 18, 1996

730 Personnel arrive onsite, and decons submersible pump

750 Personnel arrive at wells MW 37/38/39 @ Optimist park.

755 MW39, static water level is 0.00 ft from top of casing.

755 Water level of MW37 is 4.24, Water level at MW38 is 4.14.

800. Total well depth of Deep well MW-39 is 52.33 feet; Thus well column is 52.33 ft (x0.17 = 8.90); ≈ 26.70 gallons or more will be purged from Deep well MW-39.

Total well depth of MW-38 is 26.82; well column (26.82 - 4.14 =) is 22.68 (x0.17 = 3.85); ≈ 11.56 gallons or more will be purge from Intermediate well MW-38.

Total well depth of Shallow well MW-37 is 16.82, Well column (16.82 - 4.24 =) is 12.58 (x0.17 = 2.14) ≈ 6.42 gallons will be purged.

Water Measurements MW-39 (Deep)

Time	Temp	pH	cond.	Turbidity
815	66.2	6.34	~~378~~ 335	>1,000
825	66.2	6.83	318	75.1
848	67.1	7.26	304	41.5
910	67.3	7.25	303 (351)	26.1
920	64.3	7.41	298	10.5
945	66.4	7.51	300	4.12

Note: 72 gallons Total purge

(12) RJM 1/27/97

Water Measurements for MW-37 (Shallow)

Time	Temp	pH	cond.	Turb
820	67.2	6.18	500	26.7
830	67.1	6.25	453	15.8
8:45	66.7	6.34	455	10.2
9:05	66.2	6.42	451	8.70 (5 gal)
9:24	67.2	6.43	458	8.02

Note: 8.5 gallons total purge vol.

810 Slykerman calibrates pH/conductivity meters.

Water Measurements for MW-38 (Inter.)

time	temp	pH	cond.	turbidity
8:35	67.4	6.34	474	13.3
8:48	67.5	6.43	527	3.51
9:08	67.5	6.43	459	2.84 (7 gal)
9:21	67.6	6.36	424	1.44
9:48	67.7	6.41	403	2.43
10:10	67.8	6.46	397	1.41

Note. 14.5 Gallons Total Purge

930 Begin collecting SP-MW-37 (Shallow) VOA's collected first.

955 Sampling of MW-37 complete.

1000 Begin collecting MW-39A (Deep) VOA's collected first. (Duo collected here. [NOTE: Jewell preserves metals/cyn. portion of MW-37.

(13) RJM 1/27/97

1015 Begin collecting MW-38 (Intermediate) VOA's collected first.

1035 SP-MW-39 (or 39D) Complete

1040 SP-MW-30 complete

1050 Personnel load up equipment & return to staging area to pick samples & equipment.

1145 Team will ship samples at Fed Ex.

1145 F. Jewell & J. Slykerman Depart site for Atlanta.

(14) RJM 1/27/97

BVSPC Personnel: R. Mangum
Weather: Cool, Clear, Light Wind, Blue Sky

0805 R. Mangum arrives on site.
0807 Surveyors Planning + Development arrive on site. Crew from Planning + Development include Robert Jordan, Bobby Clemons, and Ben Eidson.
0820 Health + Safety meeting held on site.
0840 Mangum driving Planning + Development the hospital route.
0900 Return to the site. Henry Phillips of SWP is on site viewing activities.
0910 Robert Mangum and Ben leave the site for City of Wilmington Survey Office. Jordan and Clemons are going to the Port Authority to locate survey monaments.
0930 Mangum and Ben secure site map copies at the City of Wilmington survey office.
0955 Mangum and Ben return to the site. Henry Phillips is leaving the site.
1015 Jordan and Clemons return from the Port Authority.
1020 Begin setting up to survey the survey marker near the boat slip, on the land strip between slips.
1114 Surveying continues.
1310 Leave site for lunch, close gate behind us.
1400 Arrive back at the site.
1410 Resume surveying. The following wells are being

(15) RJM 1/27/97

surveyed: SP-MW-11, 11A, 11B, 20, 20A, 8, 8A, 16, 17, 22A, 15, 40, 41, 42, 27, 24, 24A, 29, 29A, 34, 35, 36, 31, 32, 33, 28, 28A, 37, 38, 39
1625 Examined SP-MW-33 {Well Surface Casing Not Cut-off} SP-MW-32 {Well Surface Casing Not Cut-off} will photograph later, these are unacceptable products.
1740 Finished vertical survey of all 19 existing wells and the 12 newly installed. Secured well locks. Leaving site for the day.

RJM 1/27/97

(16) RJM 1/28/97

ISVSPC Personnel: R. Mangum
Weather: Cool, still, partly cloudy

0700 Mangum arrives on site. Begins preparations for taking water levels.

0740 Start taking water levels using field decontaminated electric tape.

Well #	Date	Time	(BTOC) Depth to Water	Total Depth of Well (BTOC)
SP-MW-31	1/28/97	1119	3.38'	16.75'
SP-MW-32	1/28/97	1112	3.94'	46.84'
SP-MW-33	1/28/97	1100	3.39'	55.70'
SP-MW-34	1/28/97	1154	7.54'	17.02'
SP-MW-35	1/28/97	1144	5.50'	39.14'
SP-MW-36	1/28/97	1134	5.72'	51.69'
SP-MW-37	1/28/97	1314	4.44'	17.47'
SP-MW-38	1/28/97	1320	4.36'	27.40'
SP-MW-39	1/28/97	1328	*0.10'	52.80'
SP-MW-40	1/28/97	0845	6.01'	16.96'
SP-MW-41	1/28/97	0836	5.22'	40.65'
SP-MW-42	1/28/97	0828	5.12'	67.64'
MW-27	1/28/97	0805	2.11'	7.52'
MW-8	1/28/97	0858	4.68'	21.95'
MW-8A	1/28/97	0910	4.25'	33.04'
MW-17	1/28/97	0922	5.42'	14.77'
MW-16	1/28/97	0916	5.58'	14.47'
MW-20	1/28/97	1025	3.27'	14.83'
MW-20A	1/28/97	1030	2.93'	33.17'
MW-11	1/28/97	1008	5.46'	14.26'

(17) RJM 1/28/97

Well #	Date	Time	Depth to Water (BTOC)	Total Depth of Well (BTOC)
MW-11A	1/28/97	0950	4.18'	36.39'
MW-11B	1/28/97	0956	4.07'	44.09'
MW-15	1/28/97	0940	4.50'	14.15'
22A	1/28/97	0931	3.18'	34.06'
28	1/28/97	1253	4.20'	15.43'
28A	1/28/97	1300	3.88'	27.87'
25	1/28/97	1045	2.05'	15.37'
24	1/28/97	1225	3.38'	15.18'
24A	1/28/97	1235	3.52'	36.32'
29	1/28/97	1211	3.96'	9.52'
29A	1/28/97	1203	3.22'	40.69'

Electric tape is 0.48' longer than numerals indicate to the tip for total depth. The extra 0.48' is already added in to values of total depth shown.

1000 Henry Phillips on site looking around.

1013 Henry Phillips leaves the site.

1400 Robert Mangum leaves the site for lunch.

1450 Mangum arrives back on site.

1515 Surveyors are calling the work off due to approaching thunderstorms.

1530 Mangum locks site access gate. Leaving site for the day.

RJM 1/28/97

(18) RZM 1/29/97 — BVSPC-Personnel: R. Mangum

Weather: Overcast, Windy, Cold

0720 Mangum arrives on site.

0850 (0830 RZM) Survey crew arrives onsite.

0830 Mangum calls Bob Marbury and leaves a message updating Bob on the status of our work.

0845 Counting drums (216) in the onsite temporary fenced area.

0920 Henry Phillips is onsite, driving his truck along the perimeter of the site.

0938 Light sprinkling of rain begins.

1020 Mr. Phillips (SWP) leaves the site.

1030 Surveying continues on Woodbine Street and @ the North Carolina Port Authority. Rain increases to a drizzle.

1105 Sleet conditions begin. Mangum is assisting the survey crew in locating wells and monuments.

1330 Leave the site for lunch.

1430 Called Carter Helm to see if a complete drum inventory was previously performed. Answer is no.

1520 Arrive back @ site and begin tally of the following:

PPE / Decon Pad / Plastic Drums: ~~19~~ RZM 1/29/97

[tally marks] = 27

RZM 1/29/97

(19) RZM 1/29/97

Decon Water / Development Water / Fluid / Drilling Mud:

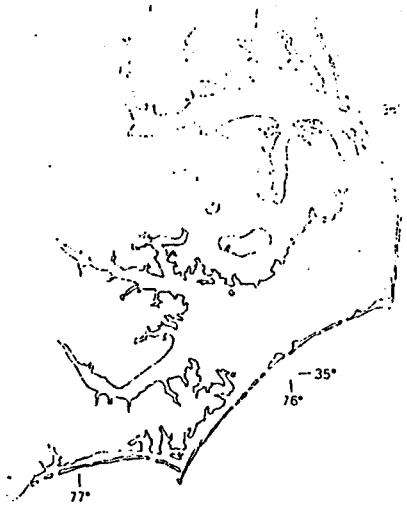
[tally marks] = 176 (177 RZM 1/29/97)

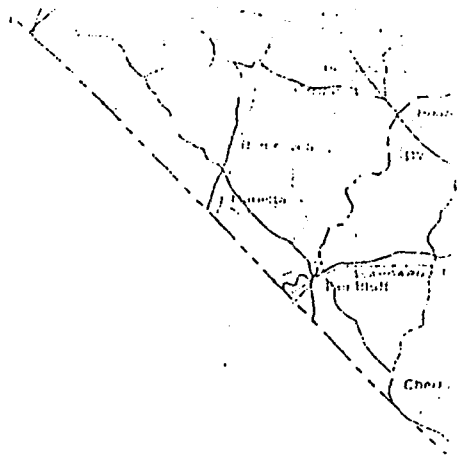
Soil Cuttings: [tally marks] = 12

Total of 216 drums counted.

1615 Mangum leaves the site after locking the drum compound gate and site gate.

RZM 1/29/97



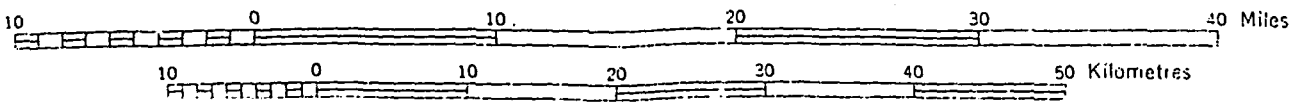


GEOLOGIC MAP OF NORTH CAROLINA

1985

Scale 1:500,000

1 inch equals approximately 8 miles



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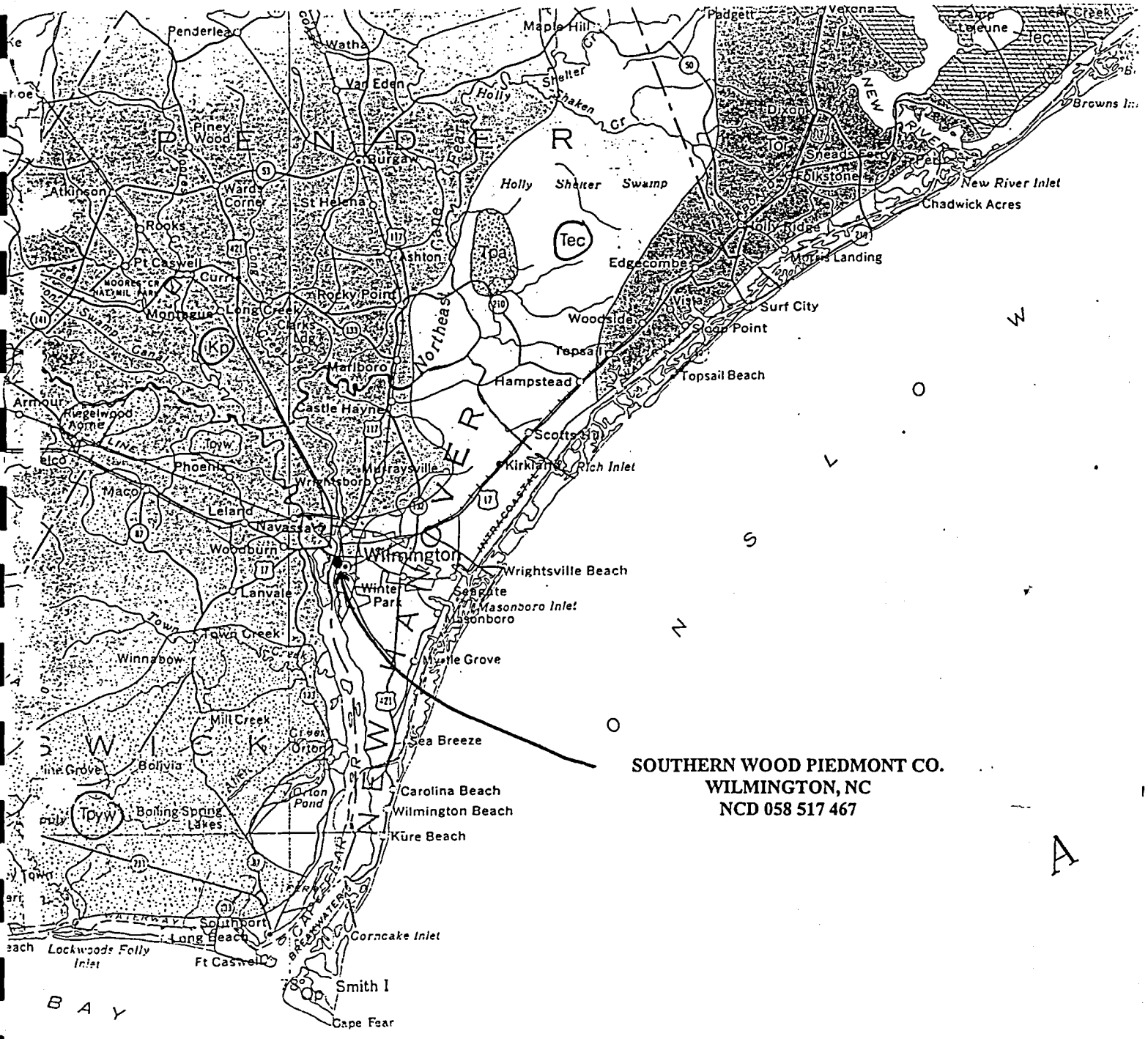

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WILMINGTON, NC
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COASTAL PLAIN

QUATERNARY

Qp — SURFICIAL DEPOSITS, UNDIVIDED — Sand, clay, gravel, and peat deposited in marine, fluvial, eolian, and lacustrine environments. Quaternary deposits not shown at altitudes greater than approximately 25 feet above mean sea level (Suffolk Scarp, in part)

TERTIARY

Tp — PINEHURST FORMATION — Sand, medium- to coarse-grained, cross-bedding and rhythmic bands of clayey sand common, unconsolidated

Tt — TERRACE DEPOSITS AND UPLAND SEDIMENT — Gravel, clayey sand, and sand, minor iron-oxide cemented sandstone

Tpyw — WACCAMAW FORMATION — Fossiliferous sand with silt and clay, bluish-gray to tan, loosely consolidated. Straddles Pleistocene-Pliocene boundary

Tpy — YORKTOWN FORMATION AND DUPLIN FORMATION, UNDIVIDED

Yorktown Formation: Fossiliferous clay with varying amounts of fine-grained sand, bluish gray, shell material commonly concentrated in lenses; mainly in area north of Neuse River

Duplin Formation: Shelly, medium- to coarse-grained sand, sandy marl, and limestone, bluish gray; mainly in area south of Neuse River

Tob — BELGRADE FORMATION, UNDIVIDED

Pollocksville Member: Oyster-shell mounds in tan to orange sand matrix, indurated locally

Haywood Landing Member: Fossiliferous clayey sand, gray to brown. Members grade into each other laterally

Tor — RIVER BEND FORMATION — Limestone, calcarenite overlain by and intercalated with indurated, sandy, molluscan-mold limestone

CASTLE HAYNE FORMATION

Tecs — Spring Garden Member: Molluscan-mold limestone, indurated, very sandy. Grades downward into a calcareous sand and laterally into Comfort Member

Tec — Comfort Member and New Hanover Member, undivided

Comfort Member: Bryozoan-echinoid skeletal limestone, locally dolomitized, solution cavities common

New Hanover Member: Phosphate-pebble conglomerate, micritic, thin; restricted to basal part of Castle Hayne Formation in southeastern counties

Tpa — BEAUFORT FORMATION, UNDIVIDED

Unnamed upper member: Sand and silty clay, glauconitic, fossiliferous, and locally calcareous

Jericho Run Member: Siliceous mudstone with sandstone lenses, thin bedded; basal phosphatic pebble conglomerate

CRETACEOUS

Kp — PEEDEE FORMATION — Sand, clayey sand, and clay, greenish gray to olive black, massive, glauconitic, locally fossiliferous and calcareous. Patches of sandy molluscan-mold limestone in upper part

Kb — BLACK CREEK FORMATION — Clay, gray to black, lignitic; contains thin beds and laminae of fine-grained micaceous sand and thick lenses of cross-bedded sand. Glauconitic, fossiliferous clayey sand lenses in upper part

Km — MIDDENDORF FORMATION — Sand, sandstone, and mudstone, gray to pale gray with an orange cast, mottled; clay balls and iron-cemented concretions common, beds laterally discontinous, cross-bedding common

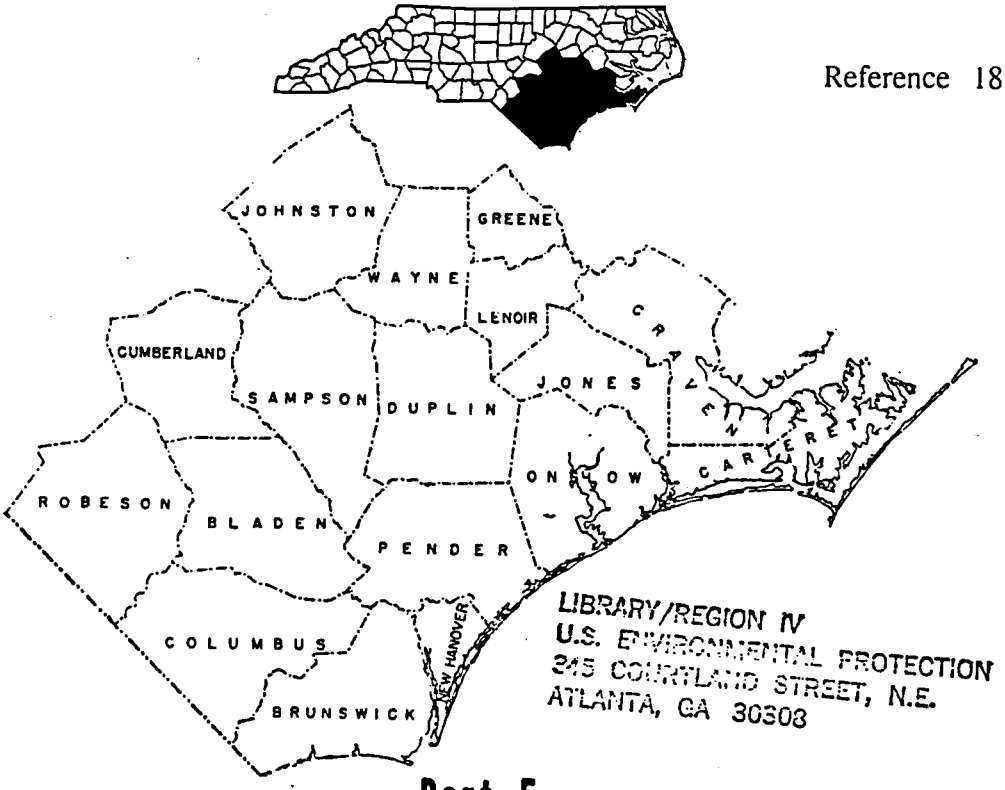
Kcf — CAPE FEAR FORMATION — Sandstone and sandy mudstone, yellowish gray to bluish gray, mottled red to yellowish orange, indurated, graded and laterally continuous bedding, blocky clay, faint cross-bedding, feldspar and mica common

NCA00255

STATE OF NORTH CAROLINA
DEPARTMENT OF NATURAL RESOURCES AND COMMUNITY DEVELOPMENT

PUBLIC WATER SUPPLIES OF NORTH CAROLINA

Reference 18



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Part 5
SOUTHERN COASTAL PLAIN

By

T. M. Robison and L.T. Mann, Jr.

Prepared by
United States Department of the Interior
Geological Survey
In Cooperation with the
North Carolina Department of Natural Resources and Community Development

Raleigh, N.C
JULY 1977

NEW HANOVER COUNTY

WATER-RESOURCES APPRAISAL

New Hanover County is in the southeastern part of the North Carolina Coastal Plain. The topography is flat and low with many swampy areas. The western and northern parts of the county are drained by the Cape Fear River and its tributaries. This river also forms the western boundary of the county. The Cape Fear River and its major tributaries are estuarine and salty in the county. The eastern part of the county is drained by streams that flow to the Atlantic Ocean, which forms the eastern boundary of the county. The average discharge of streams in the county is 1.0 (Mgal/d)/mi^2. Minimum flow and 7-day, 2-year low flow data are not available for the county. However, streams with drainage areas up to 10 square miles have been observed to go dry. Four public water supplies in the county have 500 or more customers: Wilmington, Carolina Beach, Wrightsville Beach, and Kings Grant. All of these supplies, except that of Wilmington, are from ground water. In addition, smaller public and individual water supplies and large industrial water supplies are obtained from ground water in the county. The county population in 1970 was 82,996.

The county is underlain by sedimentary deposits that thicken in a southeasterly direction. The upper sandy aquifer averages only about 50 feet in thickness. Except for a small area in northwest New Hanover County, the upper sandy aquifer is underlain by the limestone aquifer. Where present the limestone aquifer is about 50 feet thick in the northern part of the county and reaches a thickness of over 150 feet in the southern part of the county. Even where this highly-permeable aquifer is thin, well yields of a few hundred gallons per minute are obtainable. Where it is thickest, well yields of over 1,000 gal/min can be obtained. The limestone aquifer is underlain by the lower sandy aquifer. The lower sandy aquifer is about 1,000 feet thick in the northwestern part of the county increasing to about 1,300 feet in thickness in the southeast. However, the fresh-water part of the aquifer is relatively thin. The occurrence of salt water in New Hanover County is erratic, especially in the coastal areas and off-shore strands. The lower sandy aquifer might be able to produce a few hundred gallons per minute to wells at some places in these areas, but lower yields would be more prudent in order to avoid salt-water encroachment. The same statement would apply to the limestone aquifer in the coastal areas. There is an isolated occurrence of salt water in the extreme northwest corner of the county where the depth to salt water can be less than 200 feet. In this area, the lower sandy aquifer might yield only 100 gal/min of fresh water to wells. The maximum ground-water yield in the county is estimated at 1.0 (Mgal/d)/mi^2. The ground water is usually hard and may contain excessive iron or hydrogen sulfide.

LOAN COPY

PLEASE RETURN TO:
U.S Geological Survey, WRD
3916 Sunset Ridge Road
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Reference 19

GEOLOGY AND GROUND-WATER RESOURCES OF NEW HANOVER COUNTY, NORTH CAROLINA

DIVISION OF GROUND WATER

GROUND WATER BULLETIN NUMBER 17

North Carolina
Department of Water & Air Resources

Raleigh
April
1970

GEOLOGY AND GROUND-WATER RESOURCES OF NEW HANOVER COUNTY, NORTH CAROLINA

By
George L. Bain
Geologist, U. S. Geological Survey

GROUND WATER BULLETIN NO. 17

North Carolina
Department of Water and Air Resources
George E. Pickett, *Director*

DIVISION OF GROUND WATER
Harry M. Peek, *Chief*

Prepared by the
United States Geological Survey
in cooperation with the
New Hanover County Board of Commissioners
and the
North Carolina Department of Water and Air Resources

APRIL 1970

GEOLOGY AND GROUND-WATER RESOURCES OF NEW HANOVER COUNTY, NORTH CAROLINA

By

George L. Bain

Geologist, U. S. Geological Survey

Prepared by the

United States Geological Survey

in cooperation with the

New Hanover County Board of Commissioners

and the

North Carolina Department of Water Resources

Raleigh, North Carolina

1970

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February 12, 1970

The Honorable Robert W. Scott
Governor of North Carolina
Raleigh, North Carolina

Dear Governor Scott:

I am pleased to submit Ground-Water Bulletin Number 17, "Geology and Ground-Water Resources of New Hanover County, North Carolina" by George L. Bain, Geologist, U. S. Geological Survey.

This report contains the results of a detailed study of the ground-water resources made by the U. S. Geological Survey in cooperation with the New Hanover County Board of Commissioners and the North Carolina Department of Water and Air Resources. It should prove to be of much value toward the economic and industrial development of the County.

Respectfully submitted,

George E. Pickett

GEP:hbd

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GEOLOGY AND GROUND-WATER RESOURCES OF NEW HANOVER COUNTY, NORTH CAROLINA

By

George L. Bain

Geologist, U. S. Geological Survey

ABSTRACT

This report describes the ground-water resources of New Hanover County in southeastern North Carolina. The county is a part of the Atlantic Coastal Plain Province and occupies a peninsula between the Atlantic Ocean and the Cape Fear and Northeast Cape Fear Rivers. New Hanover County is a relatively flat sandy plain, few points in the county being more than 50 feet above sea level. The climate is humid; the average annual precipitation is about 50 inches.

Ground water occurs in a system of slightly inclined formations underlying the Coastal Plain. Although individual formations dip and thicken in various directions, they in aggregate, thicken in wedge-like fashion toward the coast, reaching a maximum thickness in New Hanover County of slightly more than 1,500 feet. Most of the formations are composed of unconsolidated sands and clays containing a few beds of limestone and calcareous sandstone. A veneer of sand and sandy clay of probable Pleistocene age tends to conceal the underlying sequence of rock materials of Tertiary and Cretaceous age.

The volume of water stored in the Coastal Plain formations in New Hanover County is large; however, water in all but the shallow formations is too salty for most uses.

Three major aquifers, or water-bearing beds, furnish water to wells, at least two of them being available for use in most parts of the county. They include a sandstone bed in the Peedee Formation of Late Cretaceous age, the Castle Hayne Limestone of Eocene age, and the shallow surface sands.

The sandstone aquifer in the Peedee Formation averages about 35 feet in thickness, sloping from sea level in the northwestern part of the county to about 190 feet below sea level at Wrightsville Beach. Where data are available, the aquifer is known to contain fresh water and is separated from underlying beds containing salty water by 100 to 150 feet of relatively impermeable clay. Except along the Cape Fear River and the Atlantic coast, ground water in the Peedee sandstone is under sufficient pressure to rise above sea level, and it rises to more than 30 feet above sea level in the center of the county. Some wells tapping this aquifer yield more than 400 gallons per minute, and the specific capacity in part of the county is more than 30 gallons per minute per foot of drawdown.

The Castle Hayne Limestone is irregular in thickness and areal distribution, being thicker and more extensive under the northeastern and southern parts of the county. It lies within about 30 feet of the land surface except along the coastal margin where it is somewhat deeper. The Castle Hayne has easy access for replenishment, and much water enters the limestone in the center of the county. Some wells tapping this aquifer yield more than 400 gallons per minute, and the specific capacity ranges from 3 to 80 gallons per minute per foot of drawdown.

Sand, clay, and marl of Pleistocene and Miocene age cover the land surface in all of the county. The sands comprise the uppermost aquifer in the county--that is, the water-table aquifer, except in a few places where the Castle Hayne Limestone and Peedee Formation are near the land surface. The water table commonly lies within 10 feet of the land surface and is easily reached by the common type of drive-point well.

Water of acceptable chemical quality for most purposes is available throughout the county, but a wide range in quality of water within the aquifers is common. Water in the Peedee sandstone is hard in most places, and the iron content exceeds 1 milligram per liter in the central and north-central parts. Water in the Castle Hayne Limestone is a calcium bicarbonate type ranging from moderately hard to very hard. The iron content ranges from 0.01 to more than 12 milligrams per liter. Water in the surficial sands is soft but almost everywhere is corrosive.

The current withdrawal of ground water is only a small part of the available supply, but the availability of water varies considerably from one part of the county to another. The aquifers are susceptible to salt-water encroachment because of aquifers containing salty water underlying the Peedee sandstone aquifer and because of the bordering Atlantic Ocean and brackish Cape Fear River. The present position of the interface between salty and fresh water in the ground is maintained by the volume and hydrostatic head of the fresh water. Thus, a substantial reduction in rainfall or changes in ground-water conditions created by man's activities, such as withdrawal of water through pumping, swamp drainage, or dredging which reduces the fresh-water hydrostatic head, may cause a corresponding encroachment of salt water. Salt-water encroachment may be controlled at least partially by well-field design and management. Proper practices include pumping more wells at lower rates and the use of multiple well points and infiltration galleries in shallow aquifers.

INTRODUCTION

This report describes the ground-water resources of New Hanover County. The purpose of this study was to determine the thickness, lithology, and areal extent of the water-bearing formations (aquifers), the source of replinishment or recharge to the aquifers, the direction of water movement within the aquifers, and the quantity and chemical quality of the ground water.

Fieldwork, done for this report during the period from January 1963 to June 1966, included the following:

1. Fifty auger holes were drilled to determine the lithology, thickness, age, and areal extent of the geologic formations. Where feasible, the auger holes were cased to permit water sampling, gamma-ray logging, observation of water-level fluctuations, and pumping tests.

2. Two deep test holes were drilled to determine the depth to the deeper lying Black Creek Formation, the chemical quality of water in the deeper aquifers, and the position of the fresh water-salt water interface.

3. Data on 412 wells including drillers' records, well cuttings, and water samples were collected from well drillers and owners, as well as from published sources.

4. Gamma-ray well logs were made in cased auger holes, deep test holes, and some existing wells. Electric logs of the deep test holes also were made.

5. Water-level data were collected at 5 wells equipped with continuous recorders, at 20 wells which were measured monthly, and at more than 100 wells which were measured semiannually.

6. More than 250 water samples were collected and analyzed to determine the quality of the ground water.

7. Thirty-seven pumping tests were made, and data from a few drillers pumping tests were collected to determine hydraulic characteristics of the aquifers.

8. The base-flow discharge of four small streams was measured to evaluate ground-water discharge.

9. A network of more than 150 altitude control points (accurate to $\pm$ 5 feet), necessary for geologic and hydrologic control, was established by barometric leveling.

PREVIOUS INVESTIGATIONS

No previous detailed geologic or ground-water investigations have been made in New Hanover County. David G. Thompson, U. S. Geological Survey, made a preliminary study of the ground-water resources of Wilmington (1941). A drought during the fall of 1940 had so reduced the fresh-water flow in the Cape Fear River that salt water contaminated the public water supply through the Toomers Creek intake. Thompson recommended that the surficial sand deposits of several areas on the outskirts of Wilmington be used as sources of emergency public supplies while the water intake was being extended to Lock 1 on the Cape Fear River. The sand hills area along U. S. 421 northwest of Wilmington was among those areas recommended.

The formations penetrated and the chloride concentrations of several wells in New Hanover County and vicinity were described by Clark and others (1912). Data collected by Thompson in 1941, M. J. Mundorff between 1941 and 1948, and H. E. LeGrand between 1952 and 1958 were combined in a reconnaissance report entitled, "Geology and Ground-Water Resources of Wilmington-New Bern Area, North Carolina" (LeGrand, 1960). LeGrand briefly describes the physiography and geology of the county, points out the potential of the Castle Hayne Limestone as an aquifer, and gives additional hydrologic data on the sand hills area northwest of Wilmington.

ACKNOWLEDGMENTS

The assistance of well owners, municipal and industrial officials, and well drillers is gratefully acknowledged. Particular acknowledgment is due Bill Dobo, Robert Meadows, Maurice Johnson, and H. H. Harward for furnishing well records, water-level data, and well cuttings. Auger and test-hole cuttings were processed and paleontological determinations were made by P. M. Brown, U. S. Geological Survey, Raleigh, North Carolina. Except where otherwise noted, water samples were analyzed by the Laboratory Unit, Water Resources Division, U. S. Geological Survey, Raleigh, North Carolina.

The study was initiated in January of 1963 by the U. S. Geological Survey in cooperation with the New Hanover Board of County Commissioners and the North Carolina Department of Water and Air Resources (formerly the North Carolina Department of Water Resources). The investigation was conducted under the general supervision of O. Milton Hackett, Chief, Ground Water Branch, U. S. Geological Survey. Immediate supervision was by P. M. Brown and G. G. Wyrick, former District Geologists, Raleigh, North Carolina.

GEOGRAPHY

LOCATION, AREA, AND POPULATION

New Hanover County is in the southeastern part of the Coastal Plain of North Carolina and occupies a peninsula between the Atlantic Ocean and the Northeast Cape Fear and Cape Fear Rivers. Figure 1 shows the location of the county.

The county has an area of 194 square miles. The Bureau of the Census reported the population in 1960 to be 71,742--about 370 people per square mile. Wilmington, the county seat, had a population of 44,013. Smaller towns in the county are Carolina Beach, Castle Hayne, Kure Beach, and Wrightsville Beach. Forests and farmland comprise 58 and 14 percent of the total land area, respectively. Sixty-nine percent of the residences are classed as urban.

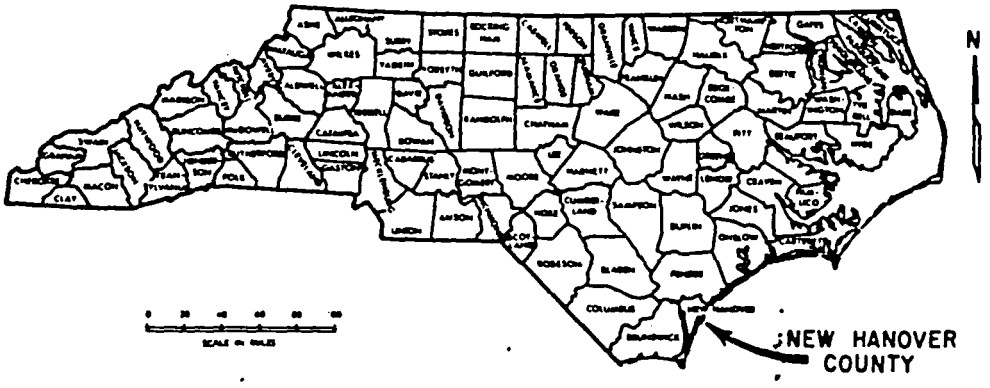

Figure 1.--Index map of North Carolina showing the location of New Hanover County.

CLIMATE

New Hanover County has a mild, humid climate. The U. S. Weather Bureau statistics for the Wilmington station show an average annual temperature of 63.8°F and an average annual precipitation of 51.29 inches for the 30-year period 1931-60. The average monthly variations in temperature and precipitation at this station are shown in figure 2. It may be observed that precipitation during July, August, and September tends to be considerably higher than in the other months. At Southport, near the southern tip of the county, the average annual temperature and precipitation for the same period of record are 64.3°F and 49.49 inches, respectively.

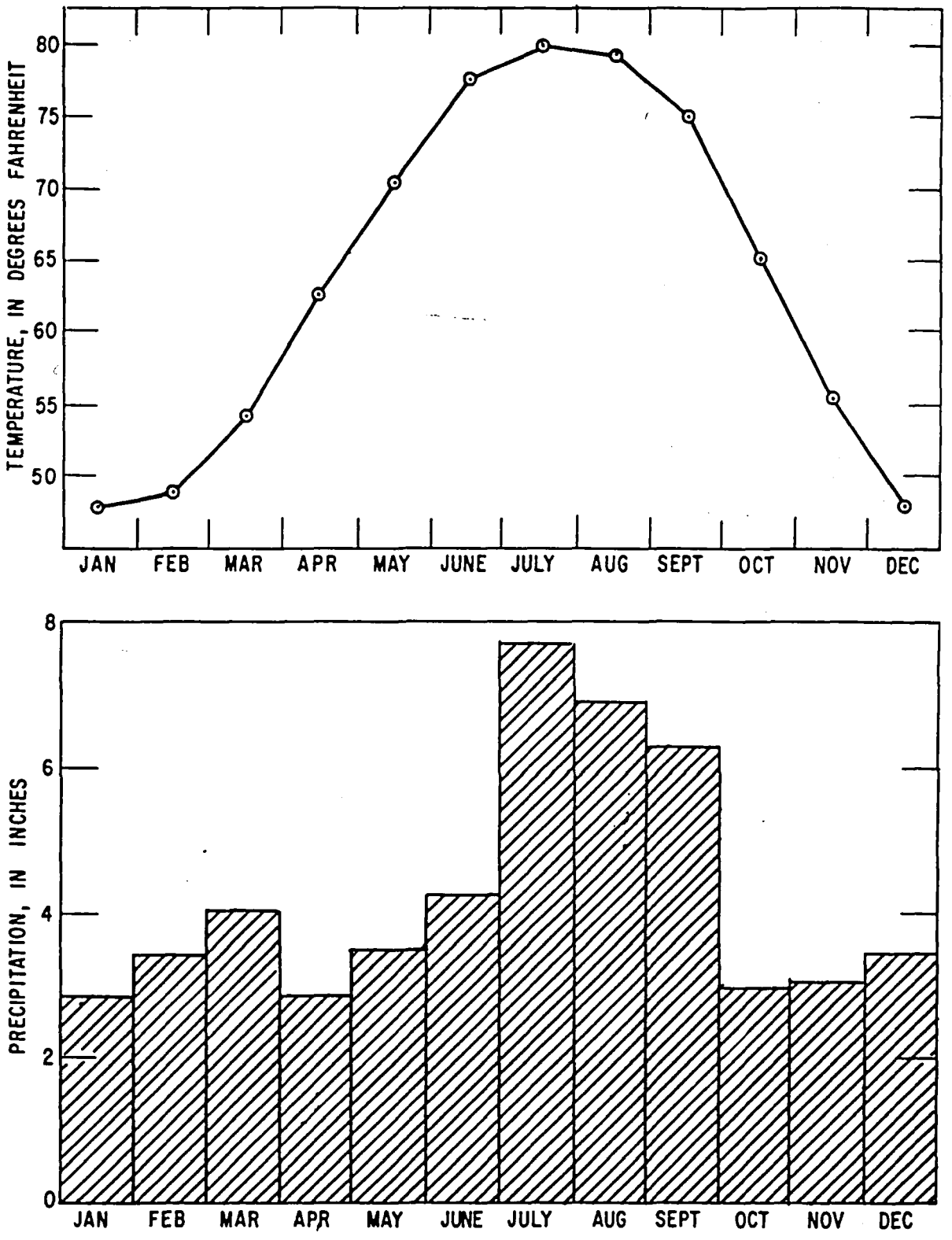

Figure 2.--Graphs showing average monthly temperature and precipitation for the 30-year period of record 1931-60 at Wilmington, North Carolina.

PHYSICAL FEATURES

The land surface of New Hanover County is a plain with a slight overall slope toward the Atlantic coast and the Cape Fear River. This plain is relatively flat in the broad interstream areas but is broken by low escarpments along the Northeast Cape Fear and Cape Fear Rivers and breached by short tributary creeks. The plain represents the part of a Pleistocene sea floor that has been exposed by withdrawal of the sea in the relatively recent geologic past. Parts of the land surface are covered with rolling sand hills. These sand hills constitute accumulations of beach sand which were shifted by the wind to form dunes. Salt marshes, tidal flats, and shallow sounds between the present-day barrier beaches and the mainland are connected to the ocean by narrow inlets.

Several topographic features are important to the ground-water hydrology in the county. The fossil dunes or sand hills extend northeastward from Fort Fisher along U. S. Highway 421 through Wilmington to and beyond the Pender-New Hanover County line. They are best developed in an area between the Cape Fear River and the Northeast Cape Fear River, northwest of Wilmington, southeast of Greenfield Lake, and south of Barnard Creek. The highest altitude in the county of 80 feet above sea level occurs on one such fossil dune system east-southeast of Greenfield Lake. Most of these thick sand deposits have no surficial drainage. Another sandy area extends northeast along U. S. Highway 17 parallel to the coast in the northeastern part of the county. This sandy area was a long bar at a time when the sea stood some 35 or 40 feet higher than it does today. To the west of this bar was a broad shallow lagoon, which is now drained by the northeast Cape Fear River. Today the area is flat and marshy. Small shallow sinks are common in the vicinity of the town of Castle Hayne and from Wilmington southward. The sinks, usually filled with water, result from the solution of near-surface limestone and coquina beds.

The altitude of much of the county is from 30 to 40 feet above mean sea level. The Talbot Terrace described by Cooke (1931) occurs at this level. Cooke also described a terrace at 25 feet above mean sea level which may be distinctive from the village of Porters Neck southward and slightly west of the sounds.

GEOLOGY

OUTLINE OF GEOLOGY

The present-day quality, occurrence, and availability of ground water in New Hanover County depend upon the physical and chemical character of the sediments beneath the county. Such characteristics as: kind of sediment, lithology, thickness, and attitude have been predetermined by the county's geologic history. When any area is inundated through a general rise in sea level or localized subsidence of the earth's crust, accumulation of marine sediment begins and erosion ceases. The kind and character of the sediment being deposited at any one place, whether limestone, sandstone, clay, shale, or sand, whether coarse or fine, or whether cemented or unconsolidated depends on many complex variables. Some variables include the kind of source material and degree of weathering, distance of sediment transport, and rate of accumulation of the shells of marine organisms.

Crustal movements along the axis of the geologic structure known as the Cape Fear Arch had a profound effect upon the type, thickness, and inclination (dip) of the sedimentary formations beneath New Hanover County and thus, ultimately have influenced the ground water. The Cape Fear Arch is now a broad gentle uplift roughly paralleling the Cape Fear River and trending southeastward through New Hanover County. Crustal movements along this axis are responsible for the lack of deposition of Lower Cretaceous sediments in part of the county, the deposition of a thick sequence of Upper Cretaceous sediments, and thin to nondeposition of the more recent Tertiary formations.

Sediment accumulation on the crystalline basement floor ranges in thickness from about 1,100 feet at Wilmington to 1,500 feet at Fort Fisher. Nearly 90 percent of the sediments accumulated during Cretaceous time when the county was on the flank of a depositional basin. These deposits, ranging in age from Cretaceous through Tertiary, are divided from oldest to youngest into the Black Creek, Peedee, Castle Hayne, and undifferentiated deposits of Oligocene(?) and Miocene age. They are overlain at the surface by sands, clays, and marls deposited during the comparatively recent geologic past.

BASEMENT ROCK

The submerged erosional surface upon which the Upper Cretaceous sediments were deposited consists of schist, gneiss, granite, and metamorphosed volcanic rocks typical of rocks which are exposed in the Piedmont Province of North Carolina. Granite occurs at a depth of 1,109 feet in well 202, which was drilled as a municipal water well for Wilmington in 1899. A well drilled during 1905-07 at Fort Caswell, across the Cape Fear River from the southern tip of the county, penetrated basement rock at 1,540 feet (Clark and others, 1912, p. 194-196). The ages of the basement rocks are unknown but may range from Precambrian(?) to Mississippian(?).

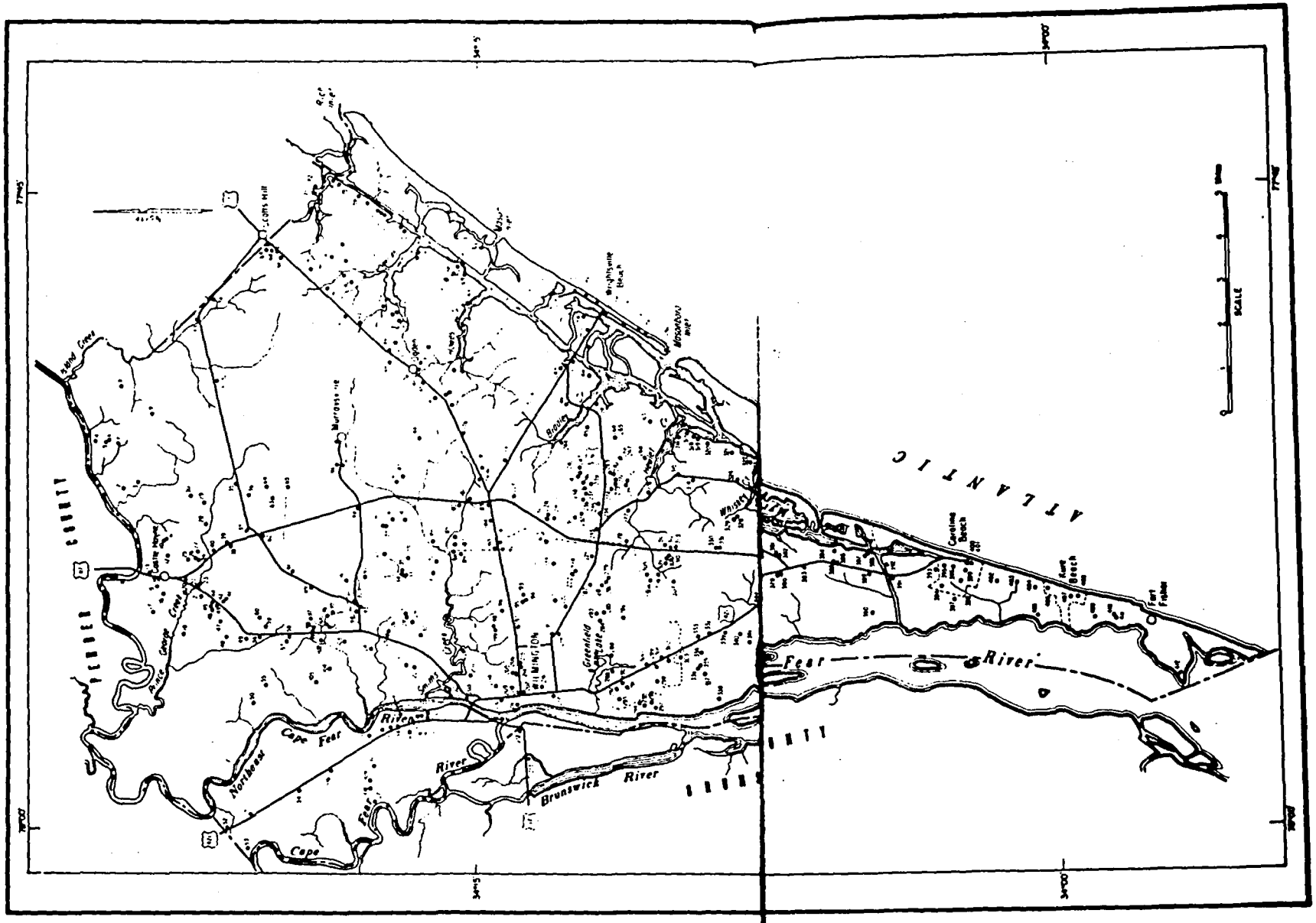

Figure 3.--Map showing the located wells.

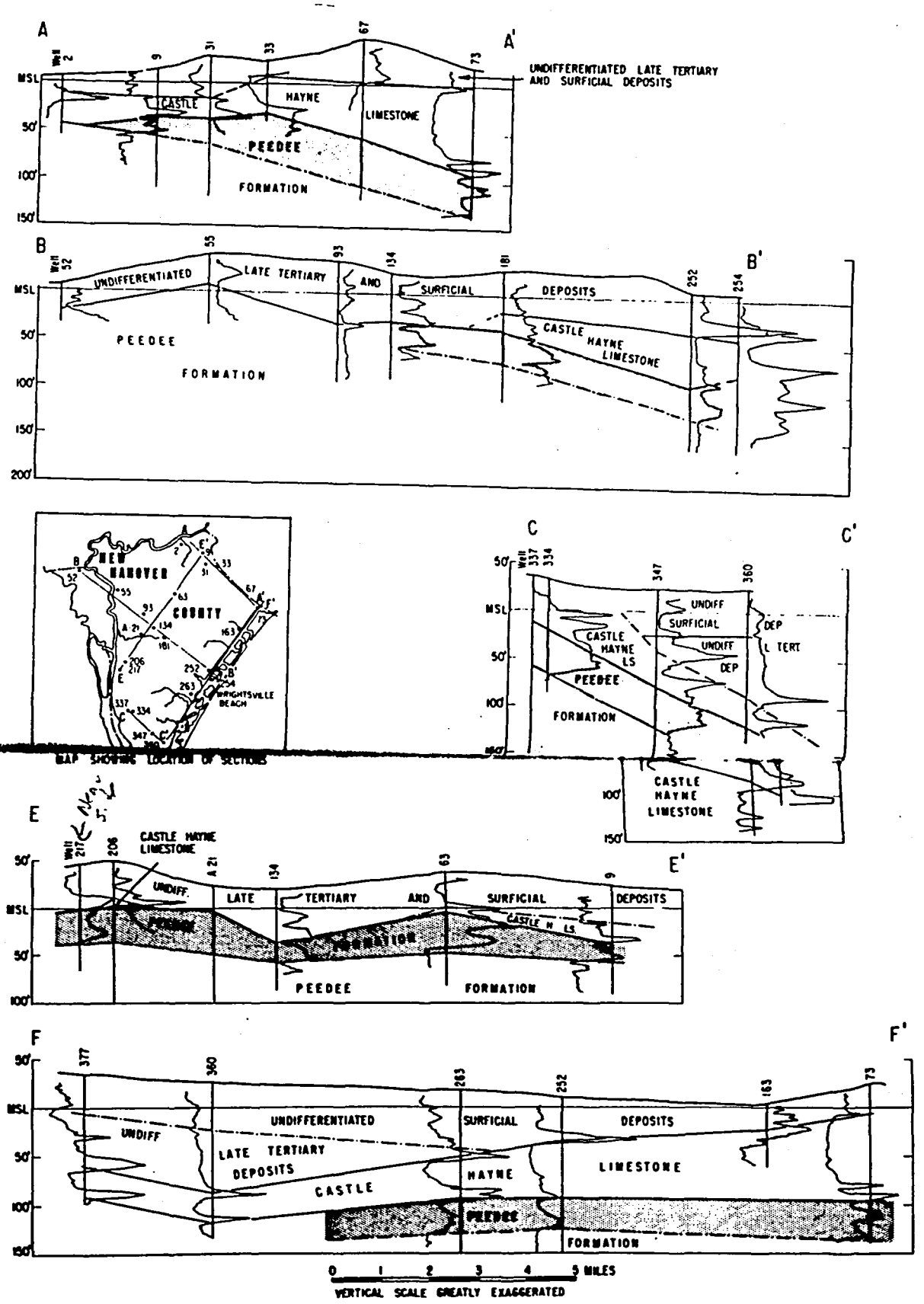

Figure 4.--Sections showing correlations by gamma-ray logs.

CRETACEOUS SYSTEM

BLACK CREEK FORMATION

The Black Creek Formation of Late Cretaceous age rests unconformably upon the basement rocks at Wilmington. Lower Cretaceous sediments and the Tuscaloosa Formation, prominent in other parts of the Coastal Plain, are not known to be present beneath New Hanover County (Brown, 1959a).

The Black Creek Formation is approximately 380 feet thick in New Hanover County. The upper and lower contacts were placed at 711 and 1,100 feet below sea level, respectively, in the Hilton Park well (well 202, see fig. 3), by T. W. Stanton (Clark and others, 1912). The top of the Black Creek was penetrated at 673 feet below mean sea level in the Murraysville test well (well 87) but was not reached in the Edwards test hole (well 347), which was drilled to a depth of 610 feet below sea level.

The Black Creek Formation is assumed to contain saline water everywhere beneath New Hanover County. Highly saline water was found in the Hilton Park well in all zones below 370 feet and in a well at Fort Caswell, Brunswick County, below 354 feet (Clark and others, 1912).

PEEDEE FORMATION

The Peedee Formation conformably overlies the Black Creek Formation in New Hanover County. It typically consists of unconsolidated greenish-gray to dark-gray silt, olive-green to gray sand, and massive black clay interbedded with consolidated calcareous sandstone and impure limestone. Glauconite gives the Peedee Formation its characteristic salt and pepper appearance. There appears to be an increase in sand and lime and a decrease in clay toward the top of the formation in New Hanover County.

The Peedee Formation in New Hanover County is 710 feet thick at well 202 and 645 feet thick at well 87, and contains four water-bearing beds of sand. The uppermost sand contains fresh water and the lower three contain brackish to saline water throughout the county. The general relationship of the Peedee Formation to the other formations in the county is illustrated in figures 4, 5, and 6. Figure 6 is a structure contour map of the top of the uppermost salt-water bearing sand. The top of the sand strikes N. 25° E. and dips toward the southeast at the rate of 10 feet per mile.

Figure 7 is a structure contour map of the top of a calcareous sandstone, the topmost sandstone in the Peedee Formation and the principal fresh-water aquifer in New Hanover County. It is discussed in a later section as the sandstone aquifer.

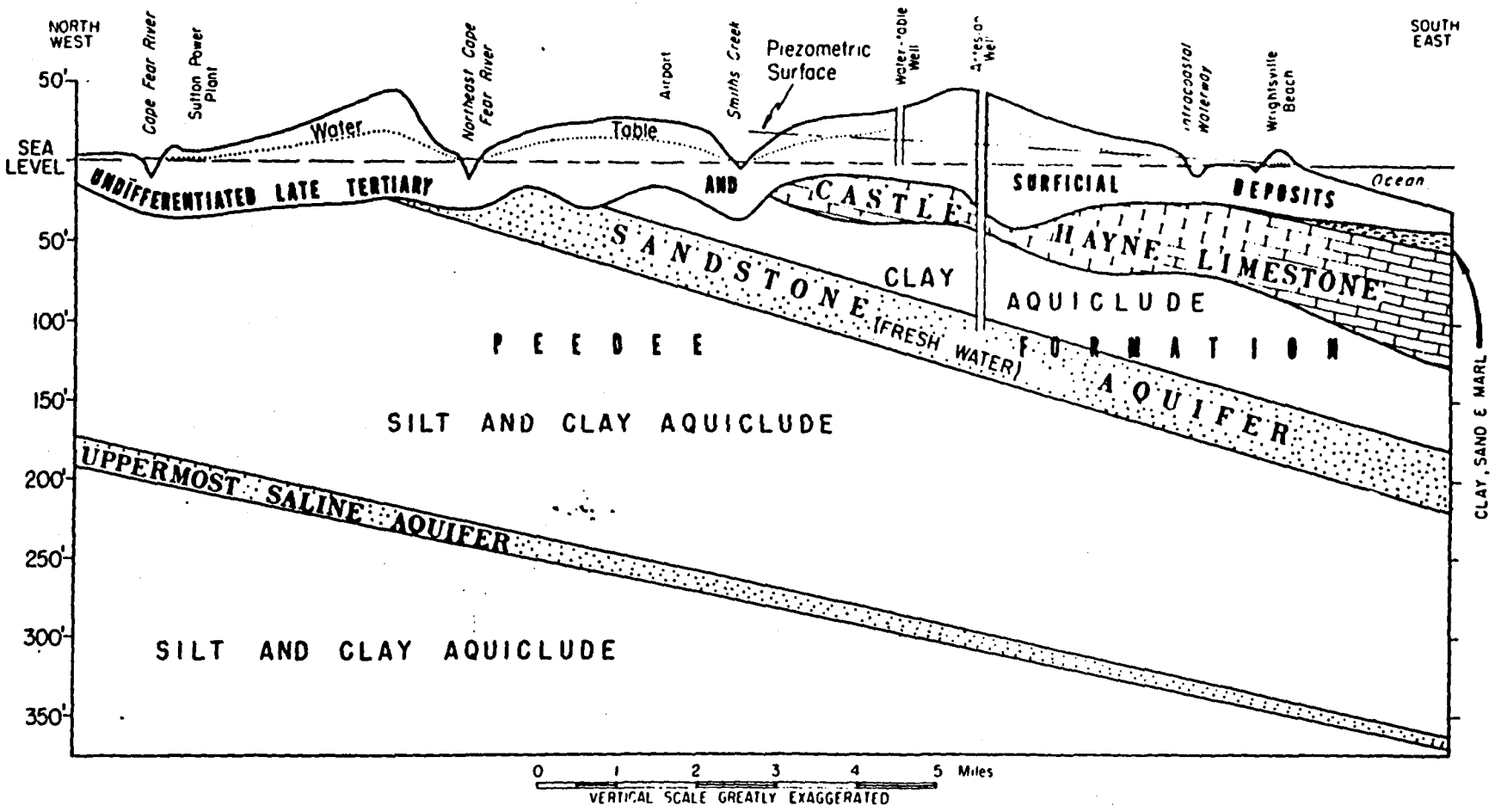

Figure 5.--Generalized diagram showing the relation of geologic conditions to the occurrence of fresh ground water.

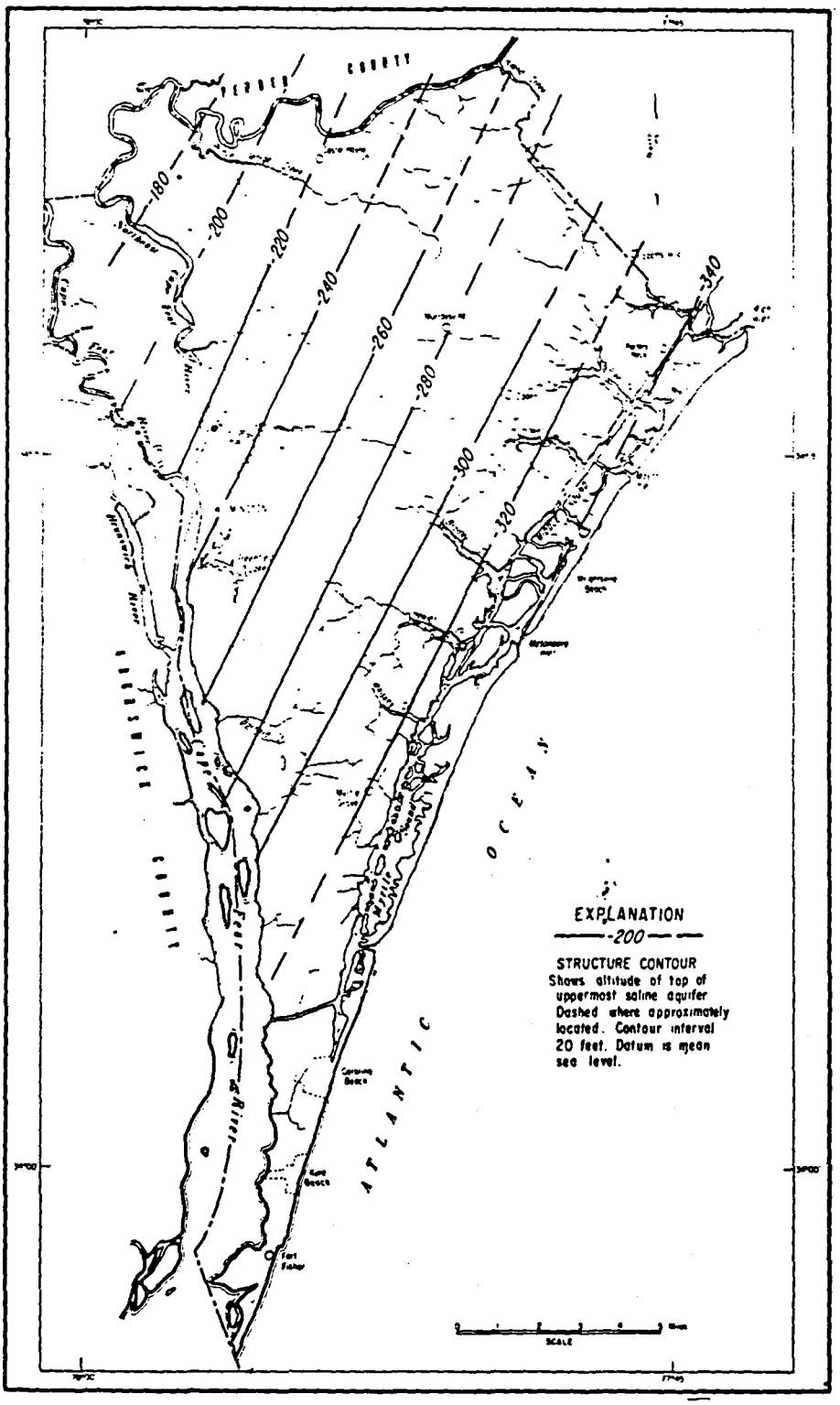

Figure 6.--Map showing the altitude of the top of the uppermost saline aquifer.

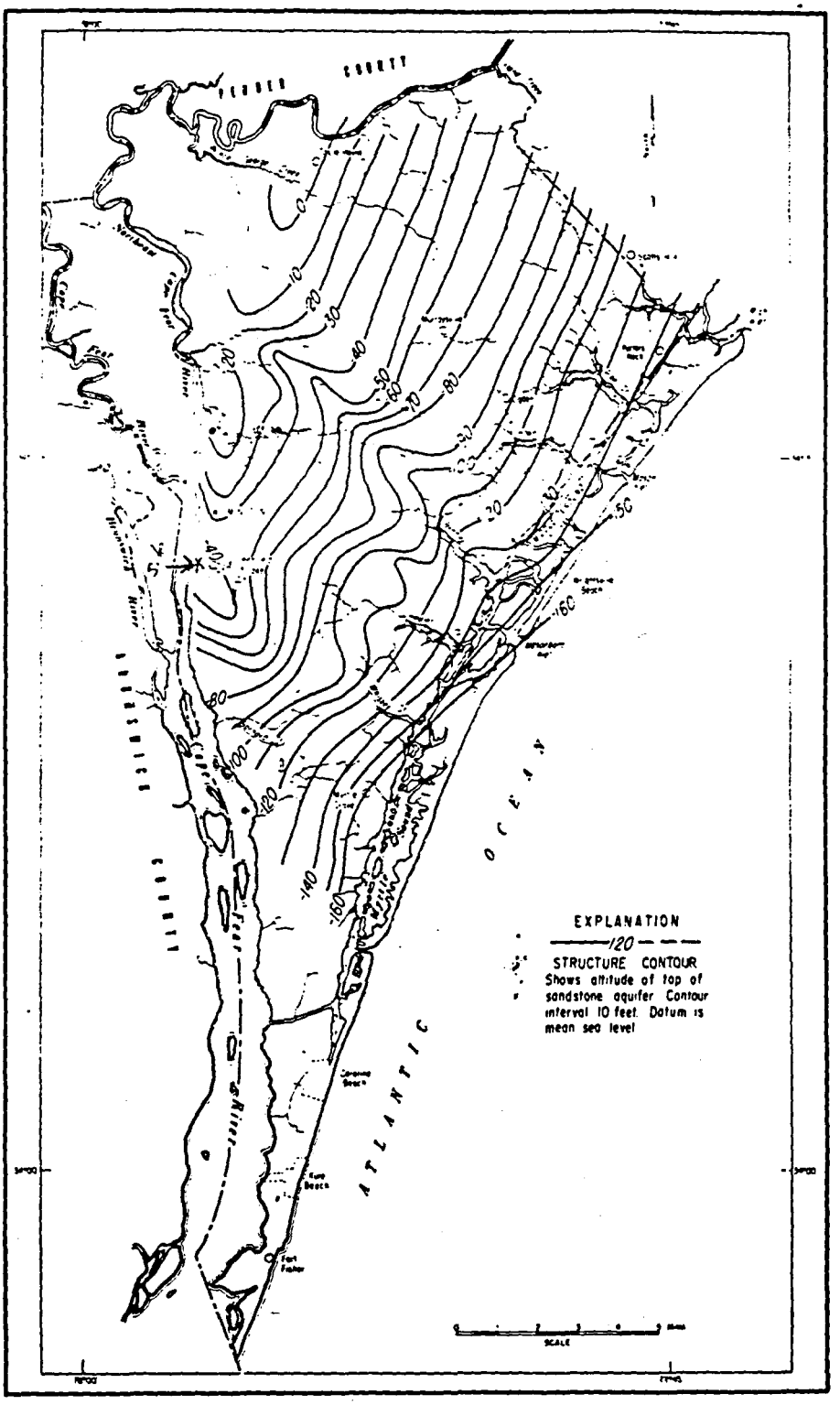

Figure 7.--Map showing the altitude of the top of the sandstone aquifer in the Peedee Formation.

All water below the altitudes shown on figure 6 is saline. All water in and above the sandstone shown in figure 7 is known to be fresh except that south of Myrtle Grove, where there are no data. Fresh water of unknown but probably limited extent and quantity was detected in well 87 in fine unconsolidated sand below the sandstone aquifer.

Figure 8 is an isopach map showing the distribution and thickness of the massive clay aquiclude lying between the calcareous sandstone and the top of the Peedee Formation. In effect, this figure shows the thickness of the impermeable beds lying between the sandstone aquifer and the Castle Hayne Limestone, the next higher aquifer.

TERTIARY SYSTEM

CASTLE HAYNE LIMESTONE

The Castle Hayne Limestone of middle and late Eocene age (LeGrand and Brown, 1955) was first described by Miller (Clark and others, 1912) at a quarry near the intersection of Prince George Creek and U. S. Highway 421 at the town of Castle Hayne. Rocks of Paleocene age were not deposited in the county because of erosion or nondeposition upon the elevated Cape Fear Arch. Thus, the Castle Hayne Limestone unconformably overlies the channeled and eroded upper surface of the Peedee Formation.

The Castle Hayne Limestone is quite variable lithologically, consisting of shell, marl, sand, and limestone. A complete geologic section in New Hanover County includes:

A. A basal sandy shell conglomerate containing much reworked material from the Peedee Formation. It is discontinuous in occurrence because it was deposited in channels on the top of the Peedee Formation. It is approximately 30 feet thick in the Superior Stone quarry near the town of Castle Hayne.

B. Above the basal shell-conglomerate is a glauconitic shell limestone. It is light-gray toward the top and yellow and dolomitic toward the bottom. In places it contains interbedded sand. Where the lower unit is missing the shell limestone facies rests unconformably upon the Peedee Formation. The glauconitic shell limestone thickens from a featheredge along its up-dip extremities to about 40 feet at the town of Wrightsville Beach and to more than 80 feet at the town of Carolina Beach.

C. The shell facies is overlain by a dense, chalk-white siliceous limestone that contains phosphate at its base. This limestone, called "cap rock," by local well drillers averages about 3 feet in thickness throughout the county.

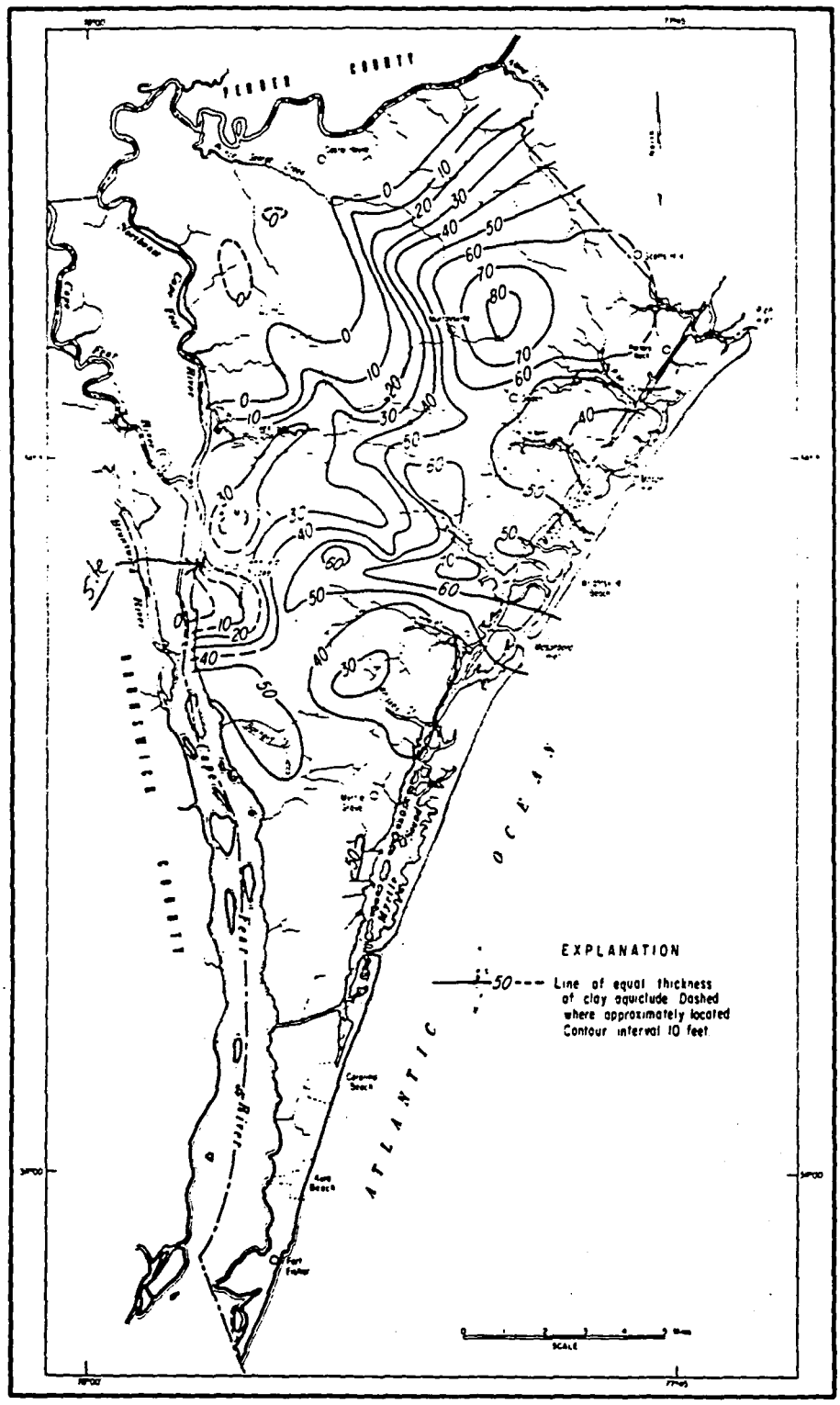

Figure 8.--Map showing thickness of the clay aquiclude in the Peedee Formation.

D. Overlying the "cap rock" is a cream to light-green, glauconitic, bryozoan-bearing "shell hash" (a coarse, braided mixture of shell fragments). This unit is generally confined to the northeastern section of the county north of a line connecting the city of Wilmington and Wrightsville Beach. South of this line the unit, if deposited, has apparently been removed by erosion. At the Ideal Cement Company quarry in the northern part of the county, where this unit is approximately 10 feet thick, it is mined for the manufacturing of cement. At Porters Neck crossroad it ranges from 55 to 80 feet thick.

The irregular distribution and thickness of the Castle Hayne Limestone (figs. 9 and 10) results from its deposition on an eroded surface of the Peedee Formation and from subsequent erosion and solution of the upper surface of the Castle Hayne. Areas in which the Castle Hayne Limestone is missing or spotty are also shown in figure 9.

The sandy, shell part of the Castle Hayne Limestone is generally a productive aquifer. Yields of individual wells in the county depend largely upon the degree to which the porosity and permeability have been increased by solution.

UNDIFFERENTIATED DEPOSITS OF LATE TERTIARY AGE

Overlying the Castle Hayne Limestone in the southern part of the county are sediments that probably range in age from late Oligocene through late Miocene. Most of the sediments in this late Tertiary sequence are phosphatic sands, silts and clays, and phosphatic limestones similar to materials in the Pungo River Formation described by Kimrey (1964) in Beaufort County, North Carolina. The upper part of the Pungo River Formation is equivalent in age to the Calvert Formation of Maryland (Brown, 1958b, p. 89) (Gibson, 1967, p. 636), which the U. S. Geological Survey currently recognizes as middle Miocene. The possibility that the lower part of the Pungo River is of early Miocene or late Oligocene has not been discounted (Brown, 1958b, p. 90) (Gibson, 1967, p. 637). According to Gibson (written communication, July 1, 1968), the sediments in southern New Hanover County "are in part facies equivalents of the phosphatic sands, limes, and diatomites of the Pungo River, but whether they belong lithologically and genetically is another question." Thus, the name Pungo River should not be applied to the deposits in New Hanover County although they are probably facies equivalents.

In the Carolina Beach area the above deposits consist chiefly of marl interbedded with light-green to dark-gray silty clay containing thin shell beds. The silty phase is replaced to the northwest by light-gray sand and sandy coquina overlain by olive-green sand. The sandy coquina, present in wells 368 and 381, is possibly of late Miocene age. Phosphate is present but is not known to be in sufficient quantities to warrant economic

ion.

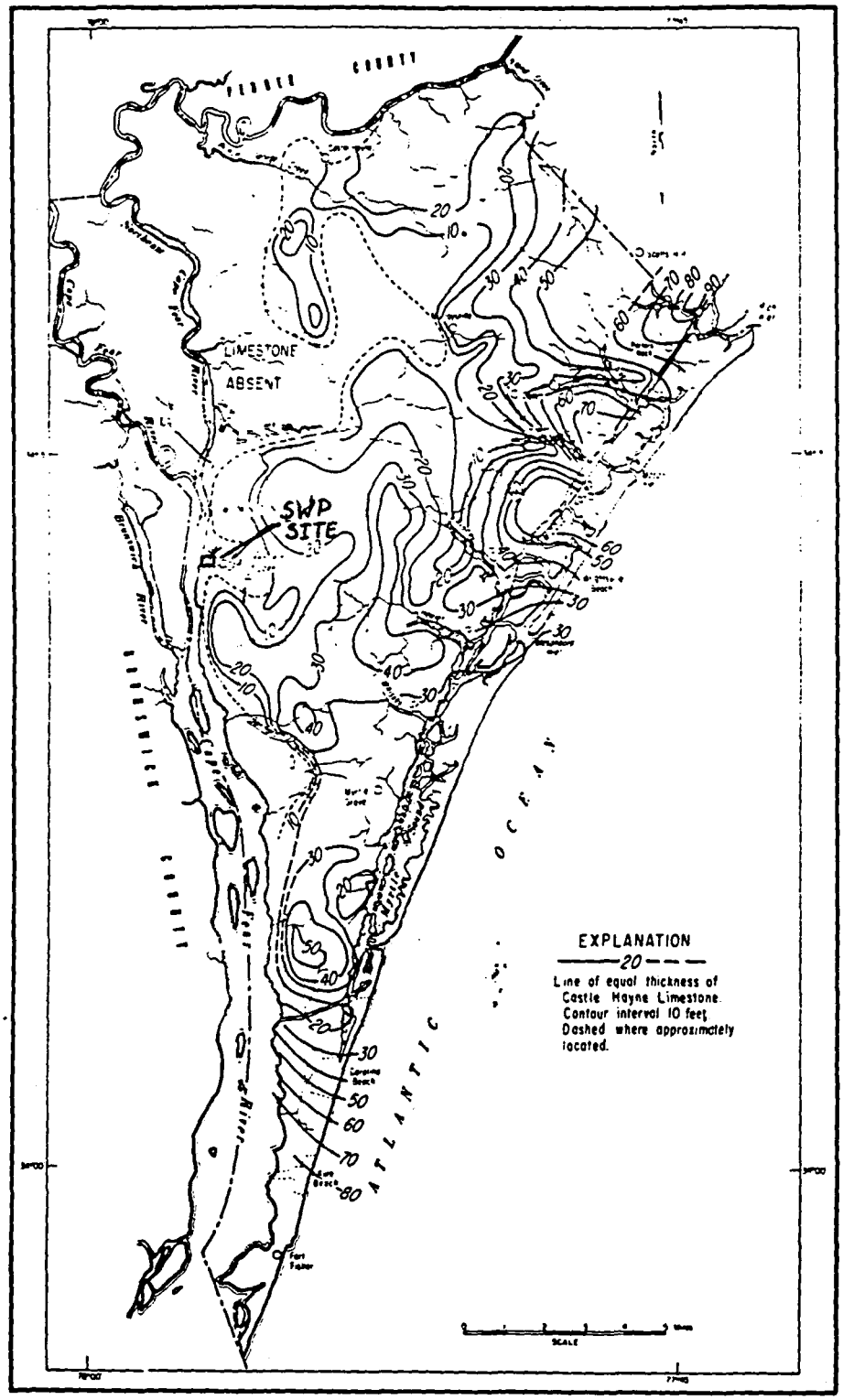

Figure 9.--Map showing thickness of the Castle Hayne Limestone.

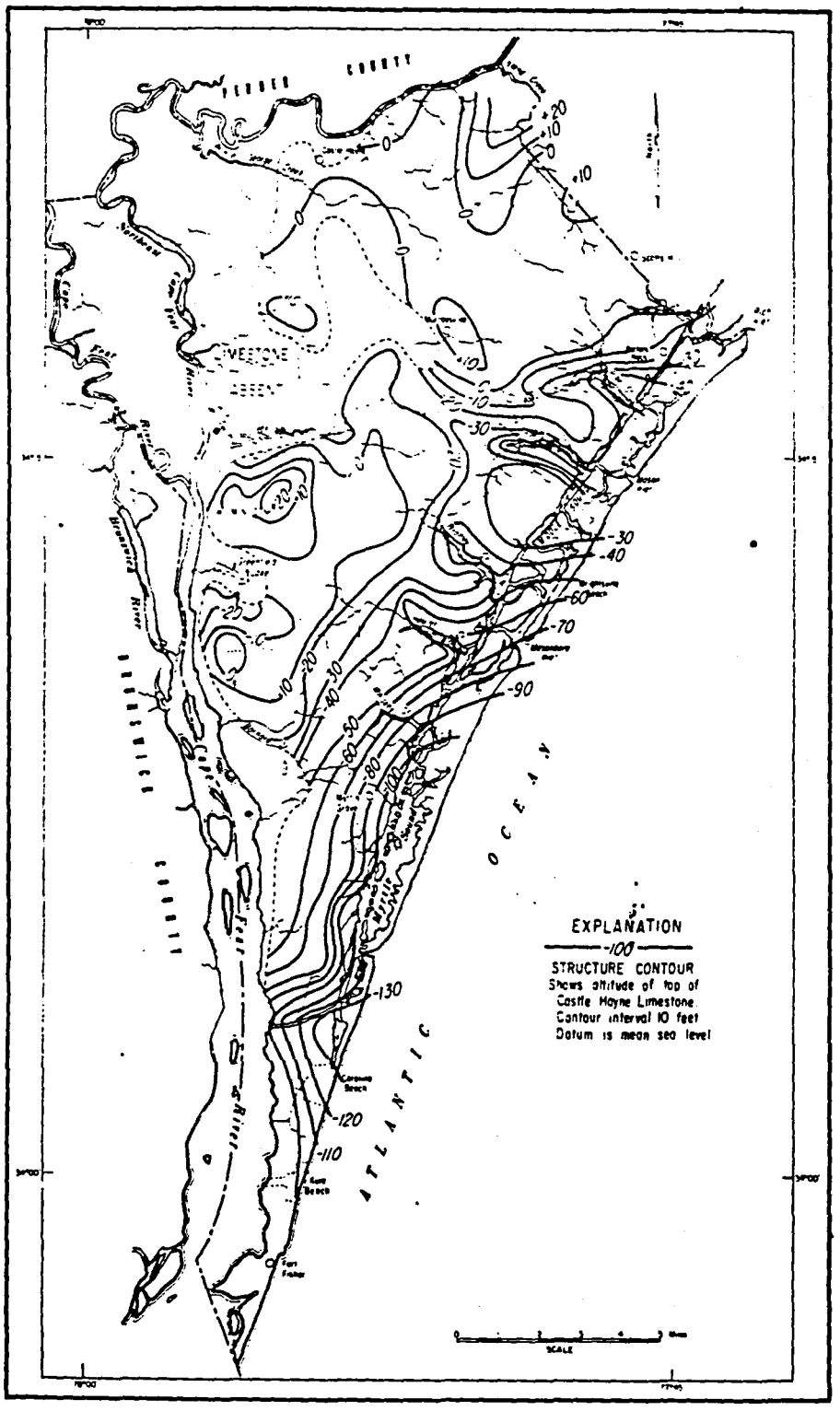

Figure 10.--Map showing altitude of the top of the Castle Hayne Limestone.

development. The lower silty part of the unit thickens southward from about 10 feet at Wrightsville Beach to 75 feet at well 394 at Carolina Beach and dips to the south-southeast and southeast at 10 to 25 feet per mile. It is overlain in the southeastern part of the county by 20 to 30 feet of fine- to medium-grained sand containing dark-gray to chocolate-brown clay beds that change southward to light-gray to olive-green clay and shell beds. This late Miocene unit is as much as 10 feet above sea level. In the north-central and northeastern sections of the county--10 to 20 feet of fine- to medium-grained sand containing a dark-gray to blue-gray clay is overlain by 5 to 20 feet of blue or gray dense clay of late Miocene age. The late Miocene clay occurs in a zone as much as 25 feet above sea level.

The silty part of the unit functions as a hydraulic barrier (aquiclude) between the overlying water-table aquifer and the underlying Castle Hayne aquifer near the seacoast.

Small to moderate water supplies are available from the sandy coquina, but only small supplies are available from the shallow sands and from the thin shell beds of this formation.

QUATERNARY SYSTEM

UNDIFFERENTIATED SURFACE DEPOSITS

Overlying the channeled surfaces of the formations previously described are deposits of clay, sand, and marl. Their age, thickness, and origin vary from one place to another. As used in this report the deposits include all of the sediments between land surface and the undifferentiated deposits of late Tertiary age. Thus, they include terraced and barrier-beach deposits, sandy coquinas (DuBar and Johnson, 1964), fossil sand dunes, stream channel deposits, and possibly thin and scattered remnants of the underlying formation. These sediments are absent in the towns of Castle Hayne and Wilmington, where the underlying limestone is exposed, but are as much as 70 feet deep near the Cape Fear River west of Myrtle Grove.

Eastward from a line connecting Fort Fisher, Myrtle Grove, and Wrightsville Beach, the base of these surficial sediments rests upon silt, clay, and shell beds of the underlying deposits of late Tertiary age. In the northwest one-third of the county they rest upon the Peedee Formation where the Castle Hayne Limestone is missing as shown in figure 10. Between the above areas they rest upon the Castle Hayne Limestone.

The surficial sediments may be divided into the following oversimplified or generalized categories:

1. In the central and western parts of the county, 0 to 35 feet of coarse, clean, nonfossiliferous quartz sand generally from 0 to 30 feet below sea level. Reference to figures 10 and 11 shows that the coarse sand occurs where the Castle Hayne is missing, or more specifically, in

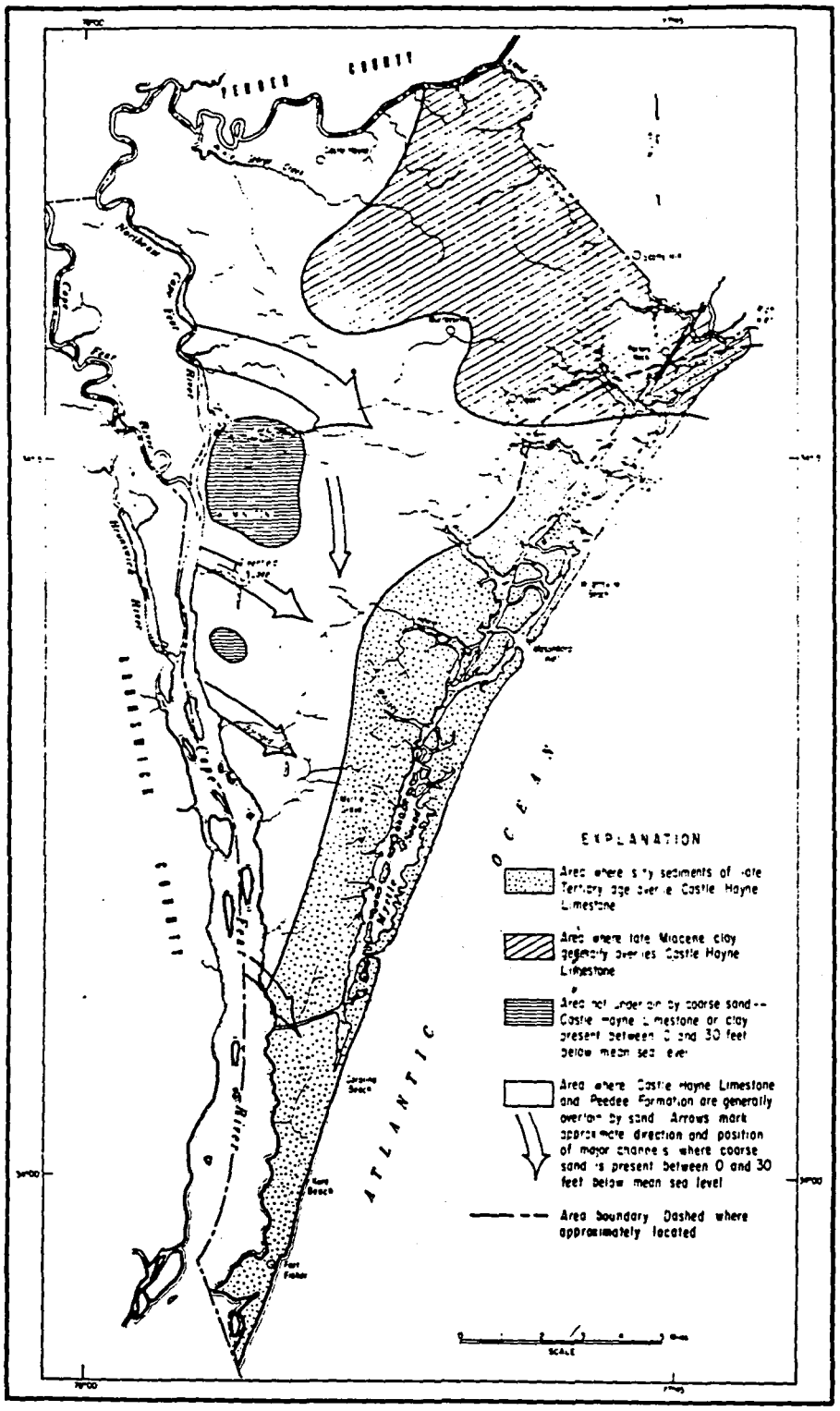

Figure 11.--Map showing the geographic distribution of Miocene clay and sand and Pleistocene(?) coarse sand.

channels cut into the surfaces of the Peedee and Castle Hayne Formations. Although there is no direct evidence, the sand is probably of Pleistocene age.

2. Throughout the county 0 to 60 feet of fine- to medium-grained Pleistocene sand tend to cover underlying clays and sands. The sandy veneer includes the commonplace surface sand and the fossil dunes and beach bars. Where swampy the sand is dark brown or black with humic material, and where well drained it is tan to gray white. Sandy coquina and marl beds occur at shallow depths in the sand along the present-day coast and mark the sites of Pleistocene beaches and inlets. As much as 20 feet of red clay and sandy clay overlie the Castle Hayne Limestone along Middle and Topsail Sounds. At a few isolated spots the surface material is a weathered product of the Castle Hayne Limestone or Peedee Formation.

The occurrence and distribution of the above sands and clays affect the water yield potential of various parts of the county. Moderate to large yields are available from these deposits northwest of Wilmington and south and southeast of Greenfield Lake where coarse sand is overlain by thick and extensive fossil dune deposits. Although the water in such deposits is acidic, iron and hydrogen sulfide are negligible. Small yields are available for domestic and small irrigation supplies from the finer grained and shallower surface sands throughout the county.

HYDROLOGY

GENERAL STATEMENT

The earth's vast but fixed supply of water is kept in endless circulation by energy supplied from the sun. Water evaporates from the oceans, lakes, streams, and land surfaces and is carried in the atmosphere as water vapor until it condenses and falls as precipitation. Part of the precipitation flows overland as surface runoff, a part is returned directly to the atmosphere by evaporation, a part is transpired by plants, and the remaining part enters the ground from which it eventually discharges to streams or to the coast.

Ground water occurs in the spaces between the rock particles in the zone of saturation. Where the spaces are interconnected and large enough to permit flow through them the rocks will yield water to wells. Rock units that yield water to wells are called aquifers. In New Hanover County two types of spaces that transmit and store water are: (1) the openings between the sand grains; and (2) the larger interconnected openings, created by solution of some of the calcareous cement and shell material from the limestone and shell beds. Interbedded clay sediments contain numerous pore spaces, but the pores are extremely small and the yield to wells is so small that they are not considered to be aquifers.

Ground water not evaporated to the atmosphere or transpired by vegetation is eventually discharged to the streams or to the ocean. The discharge of ground water is facilitated where streams have incised their channels into, or below, the water table. The discharge of water as springs or seeps in such topographically low places creates a significant difference in hydrostatic head between the water level in the interstream and stream areas. New Hanover County is essentially a peninsula; thus the Northeast, Cape Fear and the Cape Fear Rivers serve as diffuse discharge lines along the west boundary and the coast serves the same purpose along the east boundary. The upward movement through the confining beds occurs over large areas, and through the geologic ages it has been sufficient to cause partial flushing of the original connate sea water from the aquifers.

The uppermost water-bearing unit includes the surface sand that covers most of the county to depths of 50 feet or more in places. The lower part of the surface material is saturated with water; in the upper part the water is moving downward in response to gravity. The upper surface of the saturated zone is called the water table.

All of the sediments below the water table are saturated, not only in the surface sand, but also in the underlying limestone, clay, and sand. Where beds of clay and silt (aquicludes) are impermeable enough to retard the movement of water, the water in the underlying beds of limestone and sand is confined under hydraulic pressure and is called artesian water. The height to which artesian water will rise in wells forms an imaginary surface called the piezometric surface.

Artesian water moves to discharge areas in many places along the major streams and the coast. The rate of water movement from areas of recharge to areas of discharge ranges from a few feet to as much as a few hundred feet per year.

The aquifers in New Hanover County are recharged by local rainfall. Areas of significant recharge are identified on the maps showing the piezometric surfaces as the areas having higher water levels, and on the water quality maps as the areas of lower chloride and of higher iron and hardness values. These are in the interstream areas where the topography is relatively high. Conditions for recharge are excellent in New Hanover County because most of the areas are underlain by sand.

AQUIFER CHARACTERISTICS

The quantity of water that an aquifer can hold in storage is governed by its porosity. Porosity is the ratio of volume of pore space or interstices to the total volume of the rock material and is usually expressed as a percentage. Clean, well-sorted sand may have an initial porosity as high as 40 percent, but during its transformation into a sandstone the porosity may be reduced by compaction and cementation to less than 10 percent. Clay may have a porosity of 50 percent, but because of the minute size of its pores, a large percentage of the water stored in clay is retained by molecular attraction. Consequently, clays and clayey sediments act as aquicludes and tend to retard water movement.

The permeability of an aquifer is a measure of its ability to transmit water in response to gravity or to differences in hydrostatic pressure. It is governed by the size and shape of pore spaces and the degree to which these spaces are interconnected. A rock unit that is nonporous is also impermeable. However, water may be yielded freely from rocks of low porosity if the pores are interconnected and are large enough to freely transmit water. In New Hanover County, the removal of cementing material from the calcareous sandstones and limestones by solution has increased the effective porosity and permeability of these rocks, thus increasing their water-bearing potential.

The water level in an unpumped well is referred to as the "static" water level. Withdrawal of water from a well creates a difference in head between the water in the well and that in the surrounding aquifer with the result that water flows toward the well. The surface of the water around the well assumes the shape of an inverted cone (cone of depression) whose apex is at the well. (See fig. 12.) The vertical distance between the static water level and the pumping level is called the drawdown. The area in which water levels are lowered by the pumping of a well is termed the area of influence.

The coefficient of transmissibility is the quantity of water, in gallons per day, that will move through a vertical section of an aquifer 1-foot wide and extending to its full saturated thickness under a hydraulic gradient of 1 foot per foot at the prevailing water temperature. The coefficient of storage is a measure of the volume of water that an aquifer releases from or takes into storage under a unit surface area by a unit change in head.

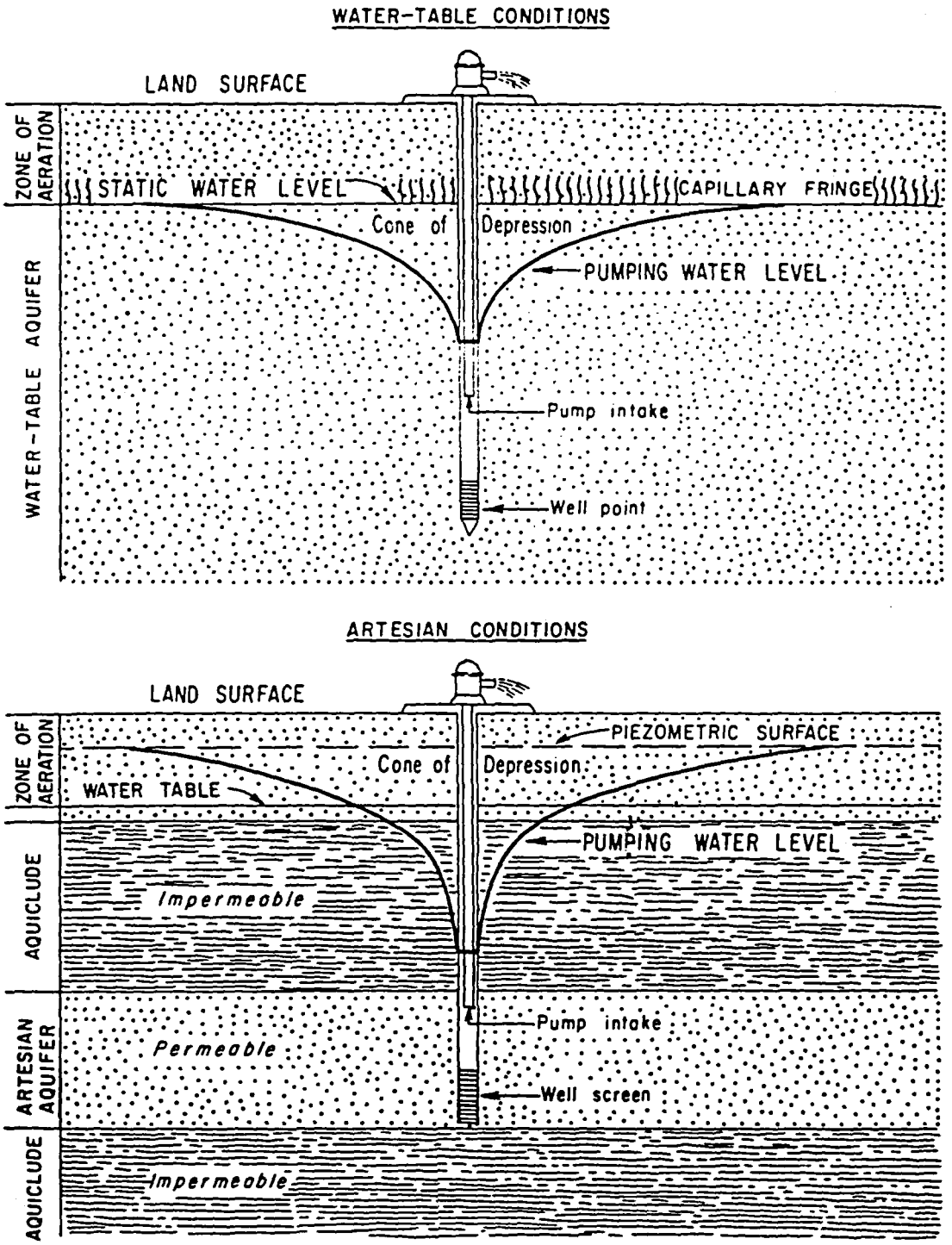

Figure 12.--Diagrammatic sections showing the effect of pumping on the water table and the piezometric surface.

The shape, size, and rate of growth of the cone of depression (and thus the yield of the well) are controlled by the transmissibility and storage coefficients of the aquifer and the rate and duration of pumping.

The specific capacity of a well is the quantity of water in gallons per minute (gpm) that a well yields for each foot of drawdown in water level after a given period of continuous pumping. The theoretical specific capacity can be calculated from the transmissibility and storage coefficients of the aquifer. The actual specific capacity is found by dividing the yield in gallons per minute by the number of feet of drawdown. Comparison of the theoretical and actual specific capacities is useful in determining the efficiency of a well.

AQUIFERS CONTAINING FRESH WATER

The deposits underlying New Hanover County may be grouped according to their ability to transmit water. The productive zones are termed aquifers, and the relatively nonproductive zones are termed aquicludes. One objective of the study was to identify and map the productive zones.

The chief fresh-water-bearing zones or aquifers in New Hanover County are: an indurated calcareous sand in the upper part of the Peedee Formation, a sandy limestone in the Castle Hayne Limestone, and beds of sand and some coquina in deposits younger than the Castle Hayne at the land surface.

Peedee Formation

The lowermost productive zone is a bed of sand in the upper part of the Peedee Formation (see fig. 7). This zone is about 35 feet thick in most of the county except where it has been partly or entirely removed by erosion; it dips to the southeast at about 14 feet per mile. It consists of quartz sand which is usually indurated with calcareous cement and is underlain by an aquiclude about 150 feet thick consisting of very fine sand and clay. Water in this zone is under artesian pressure throughout most of the county. The permeability of this sand has been increased by solution of its calcareous cement in an area that lies generally northwest of U. S. Route 17. The specific capacities of wells in this area range from 20 to 75 gpm per foot of drawdown, whereas they range from 1 to 7 gpm per foot in the eastern part of the county.

Many of the wells that tap this productive zone in the Peedee Formation are of the open-hole type, the casing being set in sandstone or on the overlying limestone. These wells are developed by using compressed air to remove loose sand, silt, and clay.

The zone is generally 10 to 25 feet below land surface in the northwestern part of the county but is more than 150 feet below land surface along the Atlantic coast. It is overlain by a clay bed that ranges in thickness from only a few feet to more than 50 feet in places. The clay bed retards the movement of water both into and out of the sand. The piezometric surface (fig. 13) is highest in the interstream areas in the central part of the county. These are the areas in which the sandstone aquifer is recharged.

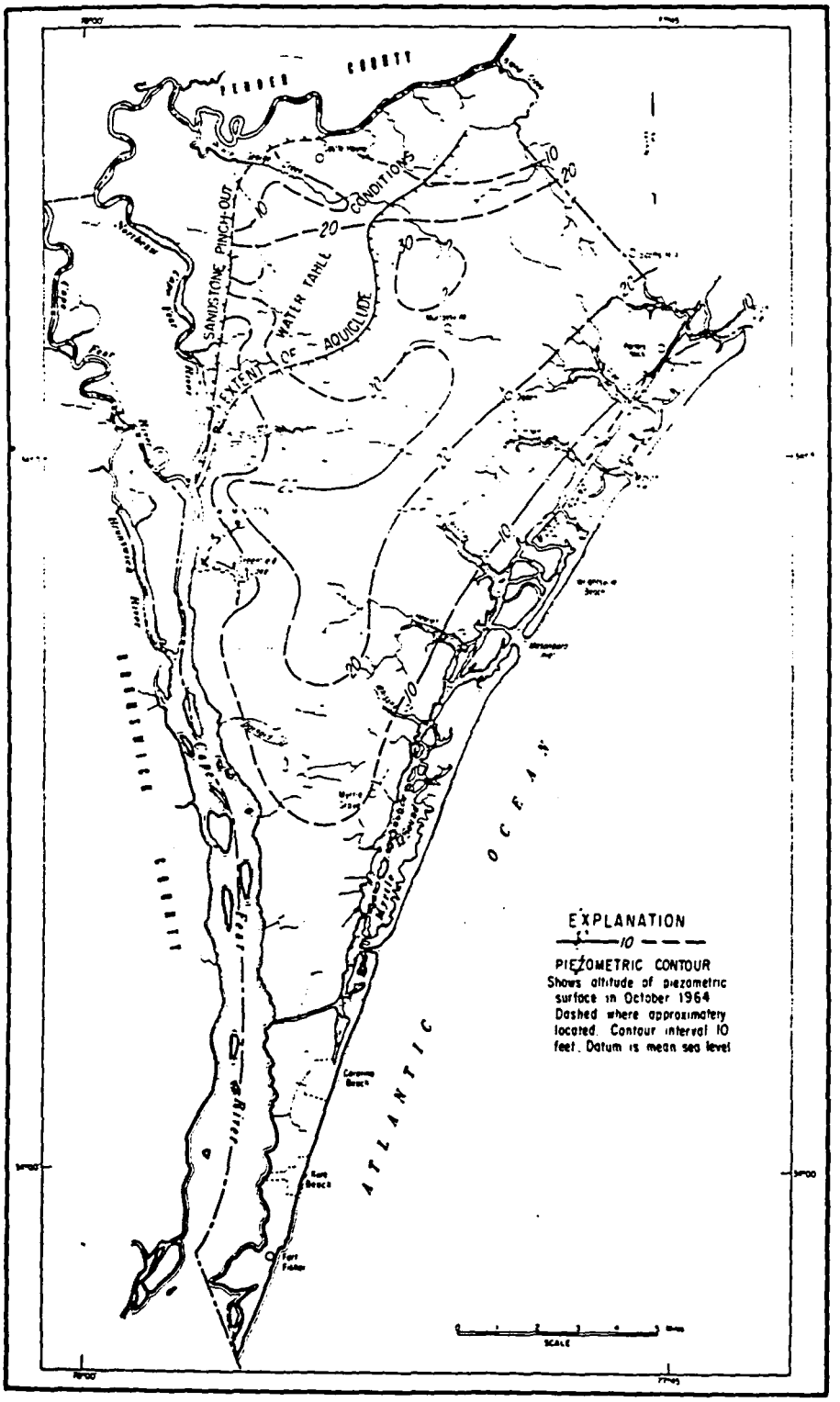

Figure 13.--Map showing the piezometric surface of the sandstone aquifer in the Peedee Formation.

This recharge occurs as water moves downward from the overlying beds. The natural discharge from the sandstone aquifer is in the major stream valleys and upward through the overlying beds along the coast.

The quality of the water from the sand in the Peedee Formation is acceptable for most uses. The hardness ranges from less than 60 mg/l (milligrams per liter) to more than 200 mg/l (fig. 14), the higher values being in the northern half of the county where the sandstone aquifer shows the greatest degree of calcium carbonate concentration. Figure 15 shows that the chloride content generally ranges from 5 to about 200 mg/l. Note that the chloride map roughly outlines the areas of recharge and discharge. The area surrounded by the 20 mg/l chloride contour approximates the area in which the Peedee sandstone aquifer is receiving recharge, and the area outside of this contour is approximately the area of discharge. The iron content in samples analyzed ranges from 0.01 mg/l to 3.0 mg/l in areas of effective recharge (fig. 16).

Castle Hayne Limestone

The Castle Hayne Limestone overlies the Peedee Formation and is a productive aquifer in much of the county. The limestone is absent in an area west and northwest of Wilmington but in other parts of the county it thickens toward the southeast. It is predominantly a sandy shell limestone, but in some places it is a hard limestone. The Castle Hayne is readily identified from well-cuttings, as it is an indurated light-colored fossiliferous limestone. Although it contains some relatively impermeable beds of marl or dense limestone, much of it is highly permeable; the permeability resulting from solution of the rock by circulating ground water (LeGrand, 1960, p. 17-18) (Mundorff, 1945, p. 50).

In the southern part of the county beds of sandy coquina and clay, probably of Miocene age, overlie the Castle Hayne Limestone. The sandy coquina yields some water to wells and probably forms a single hydrologic unit with the Castle Hayne.

Where the Castle Hayne Limestone is present in the northern part of the county, it lies near the land surface, but is more than 100 feet deep in the southern part. The thickness of the Castle Hayne varies greatly from one place to another, being generally less than 50 feet in much of the county and more than 100 feet in the southern part (fig. 9).

The water-bearing characteristics of the Castle Hayne are variable from place to place, depending on the thickness and permeability. The specific capacities of wells tested range from 4 to more than 50 gpm per foot of drawdown. The highest yields obtained from the Castle Hayne Limestone are in the area between U. S. Highway 17 and Wrightsville Beach. The water in the Castle Hayne occurs under water-table conditions in the northern part of the county. Elsewhere, however, the water may be confined beneath clay beds. Wells generally tap only the Castle Hayne in the southern part of the county where the limestone is thickest, but in the northern part, where it is thinner, the wells also generally tap both the Castle Hayne and the sand in the Peedee Formation.

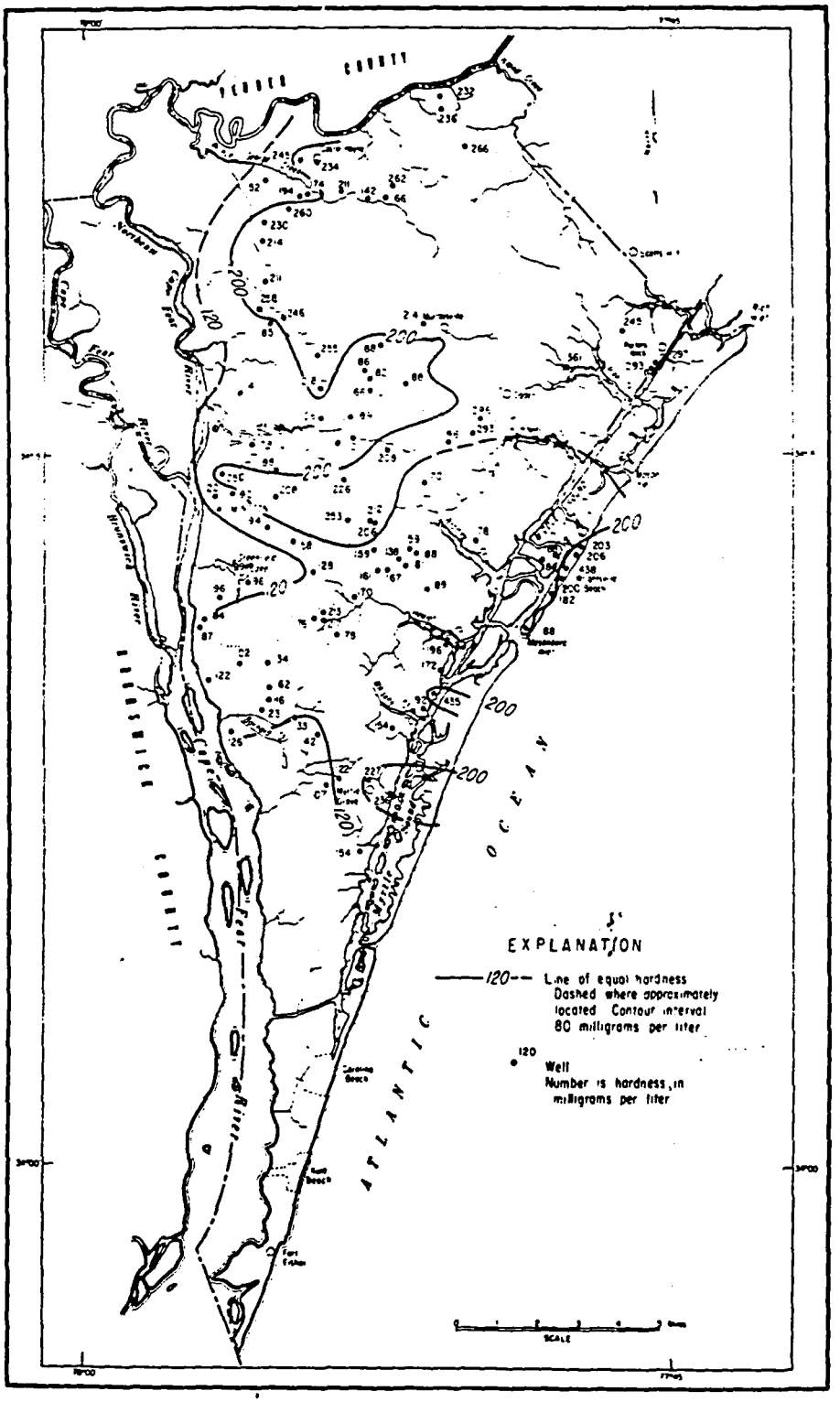

Figure 14.--Map showing the hardness of water in the sandstone aquifer in the Peedee Formation.

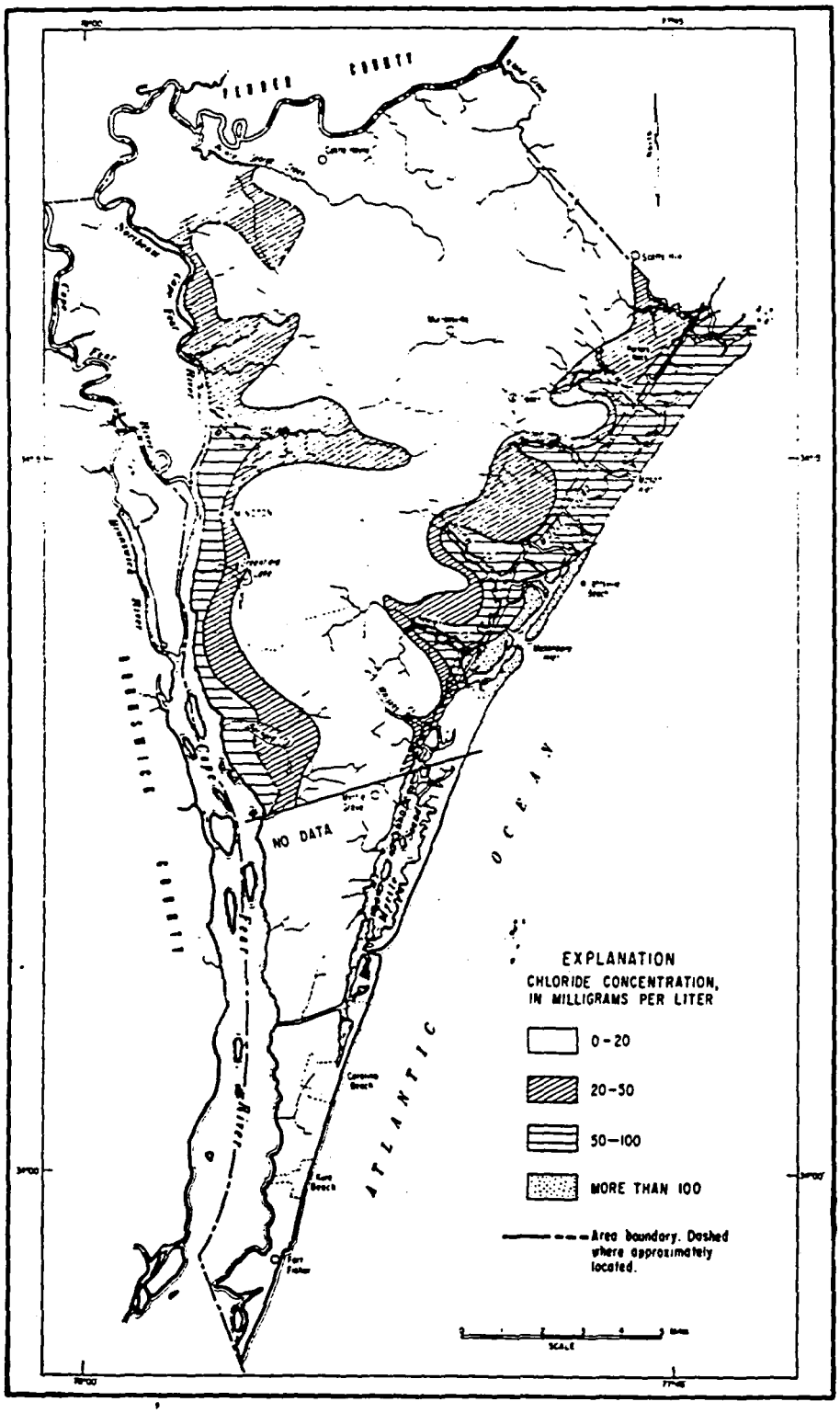

Figure 15.--Map showing the concentration of chloride in water of the sandstone aquifer in the Peedee Formation.

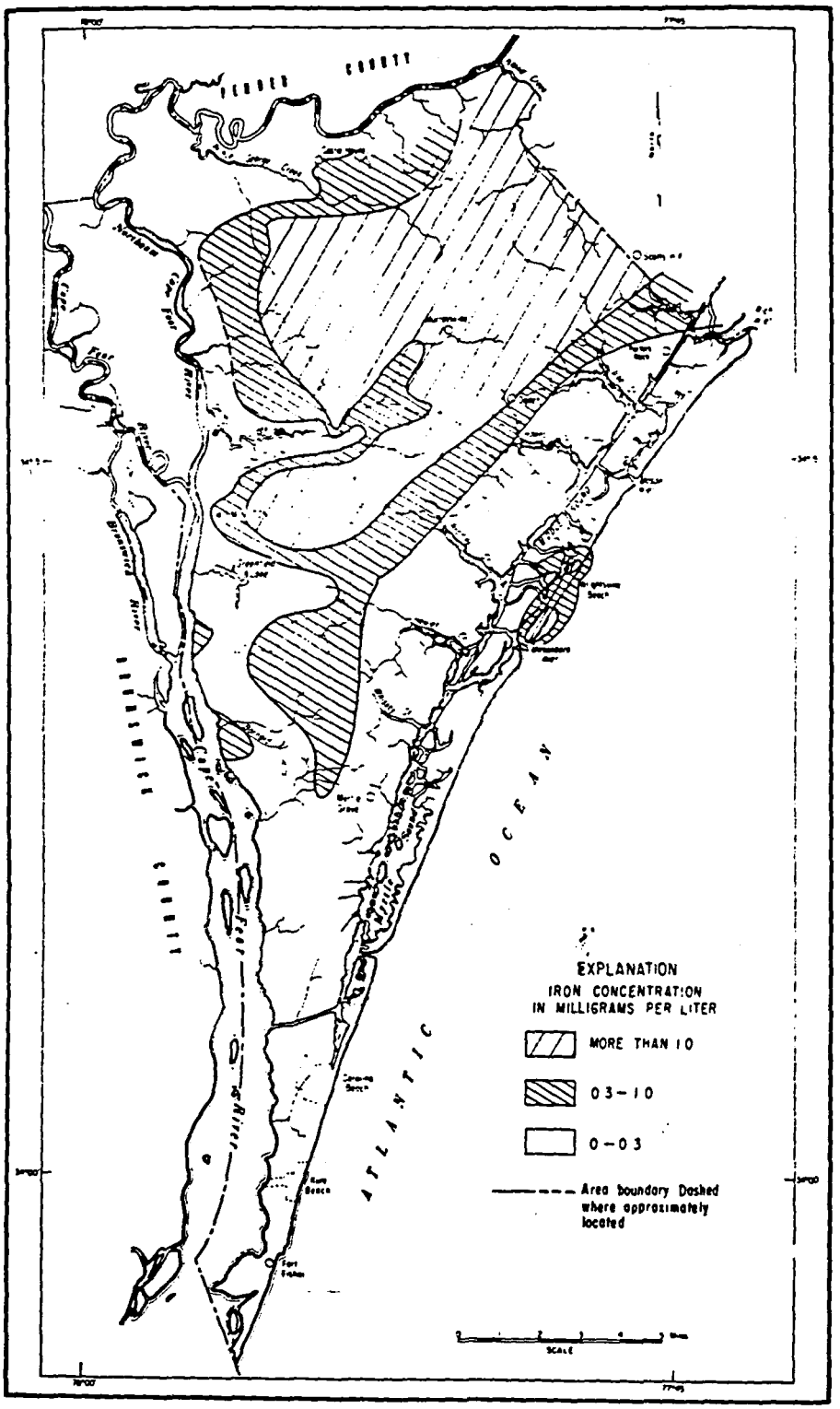

Figure 16.--Map showing the concentration of iron in water of the sandstone aquifer in the Peedee Formation.

Many wells penetrating the Castle Hayne are of the open-end type, the casing being set near the top of the formation in hard limestone. A few unscreened wells have been noted to yield water containing coarse quartz sand and fine gravel from the upper part of the formation, probably from sand-filled solution channels or cavities in the weathered surface.

The water levels in the limestone (fig. 17) are highest in the interstream areas, indicating that the formation is recharged locally; water levels are lowest in the major stream valleys and along the Atlantic coast where natural discharge takes place. Recharge of the limestone is facilitated in the northeastern part of the county where the limestone is shallow and where it is overlain by flat-lying sandy material into which precipitation readily infiltrates.

The quality of the water in the Castle Hayne Limestone is acceptable for most uses. The iron concentration of water samples analyzed ranges from 0.1 to 12 mg/l (fig. 18) and in general decreased from areas of recharge toward areas of discharge. The chloride content of the water generally is low except along the Atlantic coast where there may be leakage of sea water into the limestone. Figure 18 also shows that the chloride concentrations increase in the areas of discharge--creeks, sounds, and inlets--and are greatest along the coast from Wrightsville Beach northward. The water is moderately hard (61 - 120 mg/l) to very hard (more than 200 mg/l).

Undifferentiated deposits of late Tertiary age

Southwest of Wrightsville Beach the Castle Hayne is overlain by an aquiclude of calcareous clays, sands, and silts containing thin shell beds. This marly sequence thickens southward from Wrightsville Beach and Barnard Creek toward Carolina Beach where it is about 75 feet thick. Only very small supplies are available from the thin shell beds and cleaner shallow sands of this unit. Locally sandy coquina of irregular distribution forms a minor aquifer at or near the top of the above sequence. Specific capacities of two wells in sandy coquina (table 1) were 2.6 gpm per foot of drawdown for well 368 and 6 gpm per foot of drawdown for well 381. In four wells for which quality of water data are available, the iron concentration ranged from 0.3 to 3.1 mg/l, the chloride concentration ranged from 5 to 22 mg/l, and the total hardness ranged from 84 to 278 mg/l.

Undifferentiated surface deposits

The slightly inclined rock units previously described are overlain at the surface by beds of sand, clay, and marl. Such surficial deposits include terraced materials and related beach sands, the present day beaches, sandy coquina beds marking Pleistocene beaches and inlets, high fossil sand dunes along U. S. Highway 421 from the Pender County line to Carolina Beach, Pleistocene stream channels filled with coarse sand, and silty interstream deposits. The surface material throughout almost all the area contains the uppermost ground-water body.

The water in the surface material is under water-table conditions throughout the county. The configuration of the water table approximates the topography of the land surface.

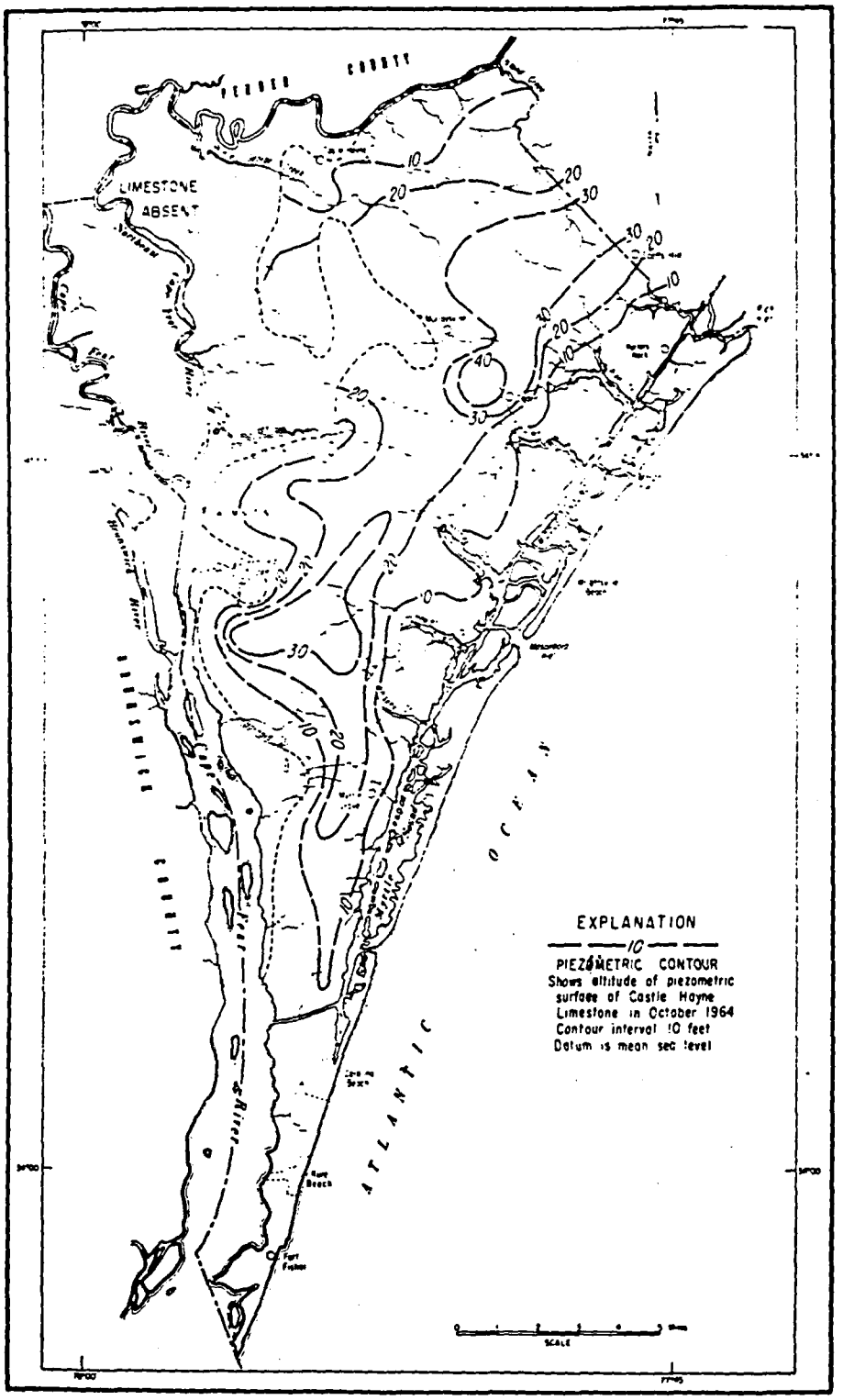

Figure 17.--Map showing the altitude of the water level in wells penetrating the Castle Hayne Limestone.

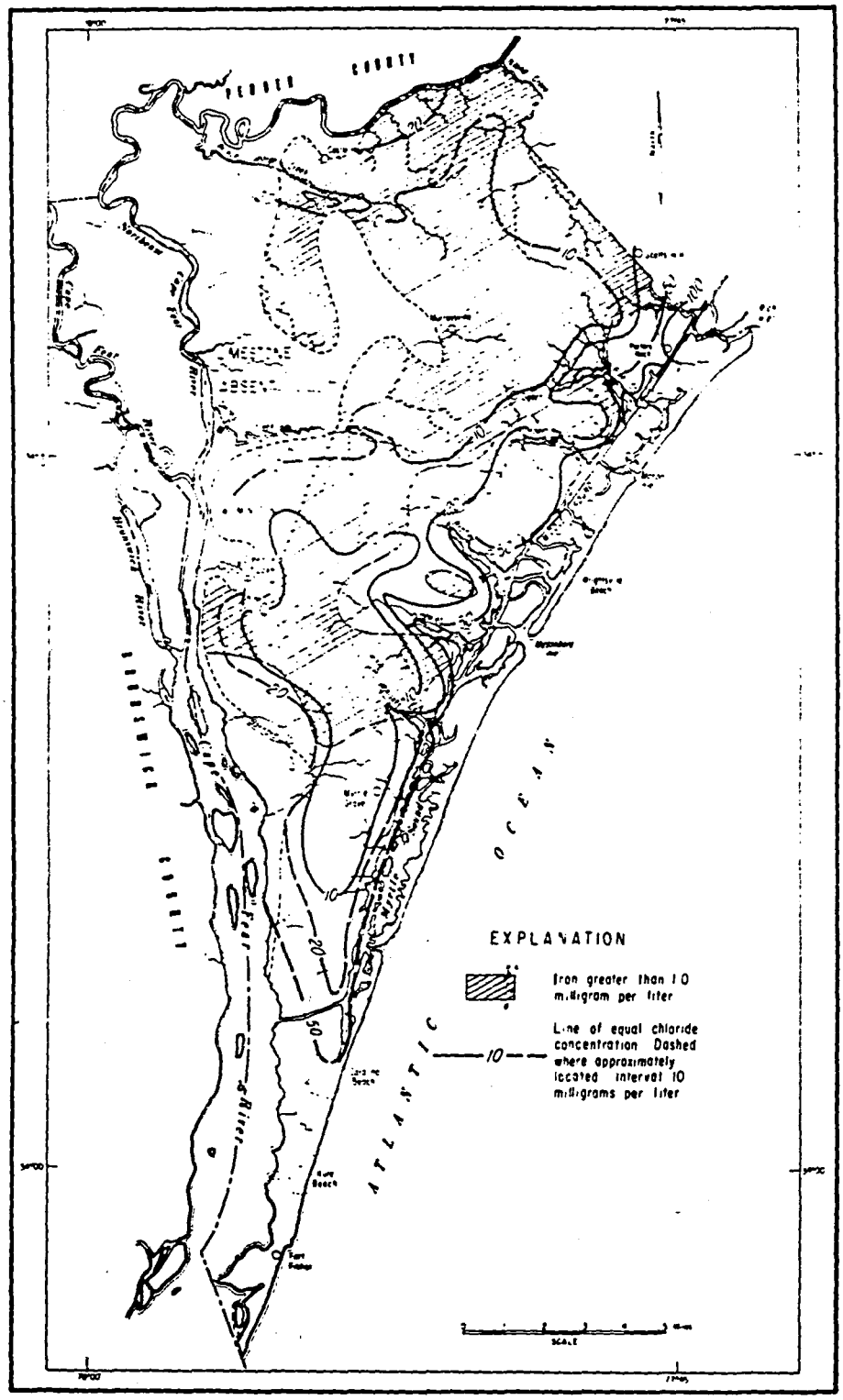

Figure 18.--Map showing the concentration of iron and chloride in water of the Castle Hayne Limestone aquifer.

The high altitude of the water table beneath topographic highs in New Hanover County indicate that the recharge areas are the broad areas between the streams. The uplands are favorable recharge areas, as they generally are flat and very sandy. Runoff is low to nonexistent. The streams have incised their channels into the surface material, and the ground water discharges as springs and seeps along the stream channels.

The thickness and water-bearing capacity of the surface material vary considerably from one site to another. The thickness determined from auger holes, ranges from less than 20 feet to about 60 feet. The water-bearing capacity depends not only on the thickness but also on the character of the material.

During this investigation the geology and hydrology were further explored through installation of 8 test sites and observation wells. The results of these tests are reported and interpreted in the following section of Hydraulic Characteristics of Aquifers.

The sand dune areas south of Wilmington are similarly underlain by coarse sand in many places, and the hydrology is thus similar. However, infiltration from the tidal creeks and the river must be prevented because the Cape Fear River estuary is quite brackish downstream from Wilmington. Brackish water extends farther up the Northeast Cape Fear than up the Cape Fear River. Therefore, all infiltration wells to be screened in the dune sand and stream deposits adjacent to the Northeast Cape Fear River between Wilmington and Castle Hayne should be managed carefully to avoid lateral salt-water encroachment.

Elsewhere, small yields are available for small irrigation and domestic supplies from the finer grained and shallower surface sands throughout the county.

The iron content in water from the surface material generally is high everywhere except adjacent to creeks, sounds, and estuaries, ranging from 0.01 to 12 mg/l. However, in the sand hills area the iron content of the water is less than 0.3 mg/l except near the rivers where some infiltration probably occurs.

The chloride concentration is less than 20 mg/l throughout the county in the surface sands. Where the sands are adjacent to parts of the Cape Fear River that contain brackish water, the risk of drawing brackish water into the sands is increased by pumping of wells.

The hardness of the water in the surface sediments ranges from soft (less than 60 mg/l) to moderately hard (61-120 mg/l) throughout most of the county.

Large yields of water have been obtained from wells in the sand hills area between the Cape Fear River and Northeast Cape Fear River north of Wilmington. A yield of 1,100 gpm was obtained from a multiple well-point installation for several weeks during construction of the Sutton Power Plant in 1952 (LeGrand, 1960). One large pond near well 105 on the east bank of the Cape Fear River is reported to have a similar high yield. Well 108 which taps the dune sand has been tested at 480 gpm at 7.0 feet of drawdown--or a specific capacity of 69 gpm per foot of drawdown. However, specific capacities of wells at the nearby Nitrex Plant range from 2 to 15 gpm per foot. Screens for naturally developed wells in these sands range from 35 to 60 slot size.

Previous investigators (LeGrand, 1960, and Thompson, 1941) have noted the permeable character, the lack of surface runoff from, and the infiltration potential of the above sand hill deposits. LeGrand (1960) suggested that about 90 percent of the prcipitation in the sand hills area soaks into the ground, and estimated that about 730 million gallons a year per square mile becomes ground water. He also indicated that because of the great permeability of the sand, the ground water discharges readily into the swamps bordering the rivers, and the water table is nowhere more than a few feet above river level. He further suggested that water from the rivers could be induced as additional recharge to the sand where water levels are lowered below river level by pumping wells and cautioned that where recharge from the river occurs, the chemical quality of the water pumped from the sand may be objectionable where the river water is brackish.

HYDRAULIC CHARACTERISTICS OF AQUIFERS

A phase of the ground-water study was designed to determine such characteristics as the coefficients of transmissibility and storage of the aquifers, and the specific capacity of wells drawing from the several aquifers. Aquifer characteristics were determined by making pumping tests on test wells, selected irrigation wells, and domestic wells; assisting well drillers in making pumping tests on wells following construction; evaluating drillers' records of previous pumping tests; comparing tidal fluctuations in wells with the corresponding ocean tides, and making pressure recovery tests on flowing wells. The test data are presented in table 1. The well numbers correspond to the numbers shown on the well location map (fig. 3).

For those tests which were of less than 24-hours duration, the specific capacities are shown as measured at the end of the tests. The adjusted 24-hour specific capacities are then tabulated in the following column, and plotted on figure 19. The coefficients of transmissibility are calculated from pumping-test data or estimated from specific-capacity data. The saturated thickness of an aquifer is given where that information is available. The approximate field permeability may be calculated at some well sites by dividing the transmissibility by the saturated thickness.

Specific-capacity data derived from the tests of 1-1/2- and 1-1/4-inch wells are affected by incomplete development, partial penetration of aquifers, pipe friction, and screen losses. Adjusted specific capacities of small diameter wells in the sand hills northwest of Wilmington differed from the observed specific capacity of the 10-inch gravel-packed wells at the Sutton Plant by a factor of about 1 to 20. Calculated coefficients of transmissibilities differed by as much as 1 to 4.

Comparison of the tested coefficients of transmissibility of wells 51 and 107 with those of established production wells in the area indicates that the coefficients of transmissibility of the coarse sand most reasonably range from 50,000 gpd (gallons per day) per foot in the north near the Pender County line to 100,000 gpd per foot in the vicinity of the Sutton Plant. The sand is also known to thicken in this direction. From the above transmissibilities and the observed ground-water levels the sand hills area is calculated to be discharging 0.88 to 2.0 mgd (million gallons per day) per square mile to the surrounding river and underlying formations. Of the 50 inches of annual precipitation 18.5 to 41 inches is contributed to ground-water recharge.

Table 1.--Aquifer test data on selected wells

Well No.	Pumping rate (gpm)	Draw-down (ft)	Length of test (hours)	Specific capacity gpm/ft of drawdown: End of test	Specific capacity gpm/ft of drawdown: End of 24-hours	Transmissibility (gpd/ft)	Storage coefficient	Aquifer[a]	Saturated thickness (ft)	Remarks
1	25.5	7.6	3	3.4	3.2	13,000 - 29,000[b]		Kpd	45	3' of $1\frac{1}{4}$" screen, #30 slot
2	30	5.3	2.5	5.7	5	7,000 - 14,000[b]	0.1-0.25	Tch	50	
4	322	45	24	7.2	7.2	10,000[b]		Tch-Kpd		
5	325	20	24	16	16	20,000[b]		Tch-Kpd		
7	325	47	24	7	7	10,000[b]		Tch-Kpd		
16	63	3.6	.67	17.5	14	25,000[b]		Tch-Kpd	40	
24	400	75	96	5.3	5.3+	8,000[c]		Tch-Kpd		
25	300	28	24	10.7	10.7	15,500[c]		Tch-Kpd		
27	200	12	24	16.7	16.7	24,000[c]		Tch-Kpd		
36	32	2.6	.3	12.7	9.0	20,000[b]	.005-.05	Kpd		
47	35	4.1	.6	9	6.5	10,900[b]		Kpd		
48	55	4.6	.9	12	8.3	11,200[b]		Kpd		
50	2.6	8.7	.3	.3	.3[c]	4,550[b]		Kpd	20	2' of 2" screen, #10 slot
51	10	4.4	.7	2.3	2.3[c]	20,000 - 30,000[b]		TQ	38	2' of $1\frac{1}{2}$" screen, #10 slot
52	12.3	5.2	2	2.4	2.4[c]	26,000 - 50,000[d]	.2	TQ	22	Transmissibility calculated from tidal effects
53	2	24	.5	.1	.1[c]	3,000[b]		TQ	27	3' of $1\frac{1}{2}$" screen, #10 slot
54	12	3.7	2	3.2	3.2[c]	22,600 - 63,500[b]		TQ	41	3' of $1\frac{1}{2}$" screen, #10 slot
63	36.5	2.6	.3	14	7.7	11,000[b]		Kpd	40+	
73	24	?	.5	1.8 ?	1.3	4,000[b]		Kpd		Only 7' penetrate

Table 1.--Aquifer test data on selected wells--Continued

Well No.	Pumping rate (gpm)	Draw-down (ft)	Length of test (hours)	Specific capacity gpm/ft of drawdown: End of test	Specific capacity gpm/ft of drawdown: End of 24-hours	Transmissibility (gpd/ft)	Storage coeffi-cient	Aquifer[a]	Saturated thickness (ft)	Remarks
82	52.5	0.65	0.3	81	60	140,000[b]		Tch	50+	
88	36	1	4	36	30	40,000[c]		Kpd		
90	53	1.3	.3	40	28	40,000[b]		Kpd	20+	
91	62	1.4	.5	44	23	25,000[b]		Kpd	30+	
106	46	12.7	2	3.6	3.6[e]	28,000 - 30,000[b]	0.15	TQ	33	10' of 2" screen, #10 slot
107	12	3.5	2	3.4	3.4[e]	60,000 - 130,000[d]		TQ	25	3' of 1½" screen, #10 slot
108	480	7	?	69		100,000[c]		Kpd-TQ	46 - 67	Gravel packed fro 33 to 53'
110	16.5	4.2	2.2	3.9	3.9[e]	70,000[b]	.3	TQ	36	
111	3.9	9.3	1	.42	.42[e]	4,000[b]		Kpd-TQ	20+	3' of 1½" screen, #30 slot
113	200	18	19	11	11	15,000[c]		Kpd	28	
114	200	13	72	15	15+	20,000[c]		Kpd	37	
115	80	20.4	24	3.9	3.9	5,000[c]		Kpd	24+	
127	7.8	.16	1	49	34	80,000[b]		Kpd	40+	
128	210	8.7	18	24.4	24	30,000[c]		Kpd	40+	
129	300	7.5	?	40		60,000[e]		Kpd	40	
131	343	9	10	38		50,000[b]		Kpd		
132	465	8	?	58		70,000[c]		Kpd		
134	64	2.6	.3	24	15	30,000[b]		Kpd		
141	73	.73	.25	100	75	100,000[b]		Tch-Kpd	38+	
175	165	<54	?	3.1+		6,000[c]		Tch-Kpd		
181	250	60	24	4.2	4.2	6,000[c]		Kpd		Gravel pack
196	100	14	?	7.1		10,000[c]		Tch-Kpd		

Table 1.--Aquifer test data on selected wells--Continued

Well No.	Pumping rate (gpm)	Draw-down (ft)	Length of test (hours)	Specific capacity gpm/ft of drawdown: End of test	Specific capacity gpm/ft of drawdown: End of 24-hours	Transmissibility (gpd/ft)	Storage coefficient	Aquifer[a]	Saturated thickness (ft)	Remarks
208	97	14.4	24	6.8	6.8	13,000[b]		Kpd	40+	
215	165	44.5	?	3.7		5,000[c]		Kpd		
218	220	20	?	11		20,000[c]		Tch-Kpd		
228	340	80	24	4.25	4.25	6,000[c]		Tch-Kpd		Gravel pack
230	360	55	24	6.6	6.6	10,000[c]		Tch-Kpd		Gravel pack
244	16.4	5.9	3	2.8	2.5	8,000[b]		Tch-Kpd		
254	60	16	.3	3.7	2.6	6,000[c]	0.001	Kpd		
260	150	20	48 ?	7.5	7.5	11,000[c]		Kpd		
262	150	90	48 ?	1.7	1.7	4,000[c]		Kpd		
290	100	15		6.7		10,000[c]		Kpd		
294	275	58	24	4.8	4.8	9,000[c]		Kpd		Gravel pack
299	144	36.7	24	4.0	4.0	7,000[c]		Tch-Kpd		
302	110	17	24	6.5	6.5	14,000[c]		Tch-Kpd		
323	50	7.6	?	6.6		14,000[c]		Tch-Kpd		
329	25	7.8	1	3.2[c]		9,000[b]		Tch-Kpd		
335	192	36	24	5.3	5.3	7,000[b]		Kpd		
341	4.7	2.4	5.4	1.95	1.8	4,000[b]		Kpd		
342	600	19.6	8	30.6	21.3	40,000[b]		TQ-Kpd		Gravel pack
343	60	15	24	4	4	6,000[b]		Kpd		
361	50	7	.17	7	4	6,000[b]		Tch-Kpd		
368	5	1.8	5.1	2.8	2.6	4,000[b]	.5	TQ	54	2' of 1¼" screen, #10 slot
397	150	33	24	4.55	4.55	7,000+ [c]		Tch		
398	153	51	24	3.0	3.0	5,000+[c]		Tch		

Table 1.--Aquifer test data on selected wells--Continued

Well No.	Pumping rate (gpm)	Draw-down (ft)	Length of test (hours)	Specific capacity gpm/ft of drawdown		Transmissibility (gpd/ft)	Storage coeffi-cient	Aquifer[a/]	Saturated thickness (ft)	Remarks
				End of test	End of 24-hours					
406	28	1.7	0.3	16.5	12	30,000[b/]	0.0001	Tch		
407	170	30	5	5.7	5.4	20,000[b/]		Tch		
410	235	23	9	10	9	20,000[c/]		Tch		
412	30	8	3	3.8	2.8	5,000+		Tch		

a/ Kpd - Peedee.
Tch - Castle Hayne.
TQ - Undifferentiated late Tertiary and Quaternary sands.

b/ Calculated from time-drawdown graph.

c/ Estimated from specific capacity and storage data.

d/ Calculated from tidal effects.

e/ Still undergoing development at end of test.

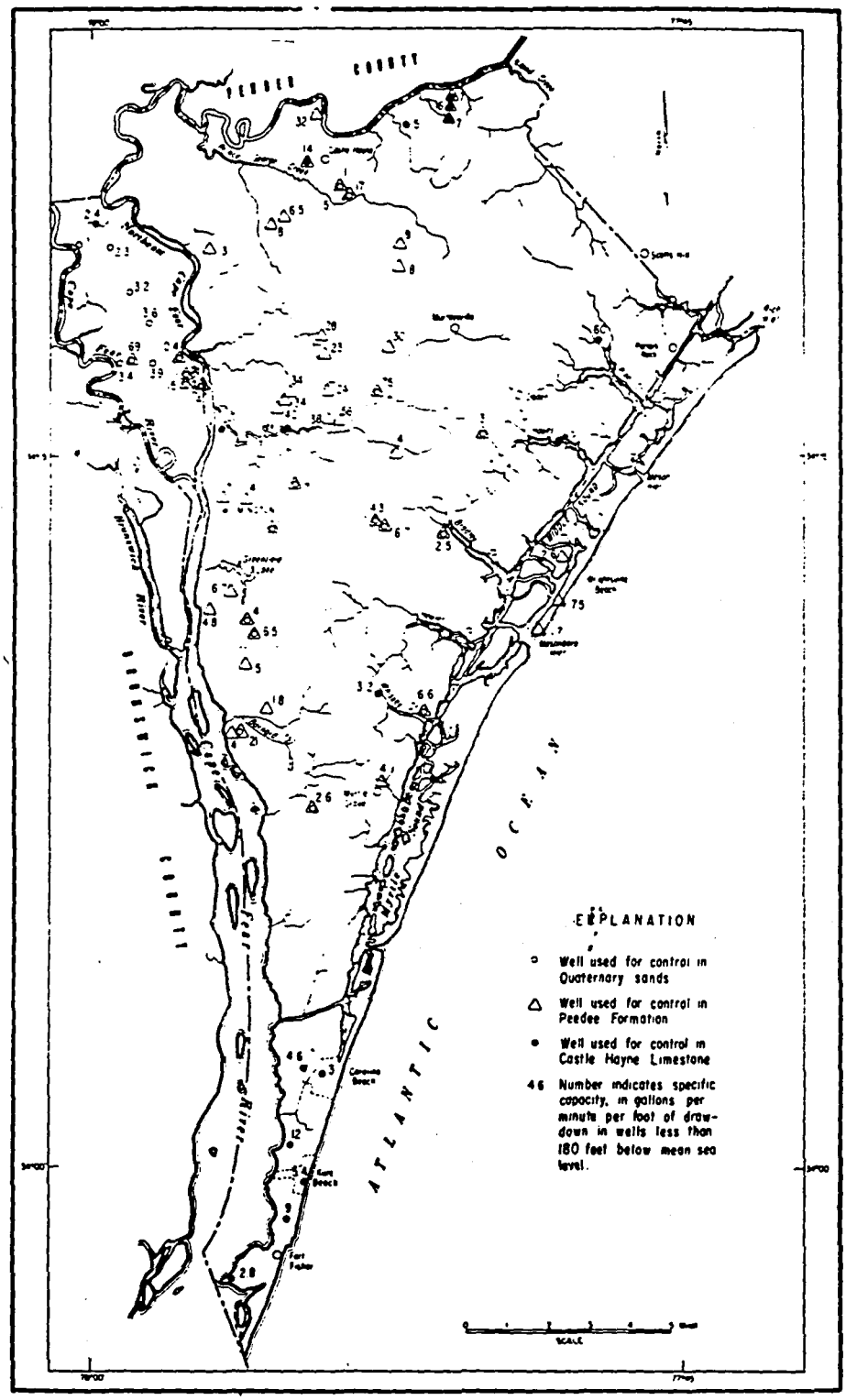

Figure 19.--Map showing measured specific capacities of wells with depths less than 180 feet below mean sea level.

The amount of ground-water discharge that can be salvaged as potable water depends upon future well-field design and development, the degree to which the area is left unpaved, and the manner of disposal of industrial wastes. The moderate coefficient of transmissibility and high coefficient of storage indicate that the coarse sand deposits can be developed using infiltration galleries, open ponds, multiple well points or large-diameter gravel-packed wells.

The data from the sand hills area northwest of Wilmington indicate that yields from wells 8-inches in diameter, gravel packed to a nominal 16-inch diameter with 20 feet of screen, and spaced at least 500 feet apart will be at least 250 gpm. Similar yields should be expected from such well-field designs in the sand-dune area south of Wilmington where underlain by coarse sand. Larger yields may be obtainable as a result of induced infiltration in areas where the sands are hydraulically connected with the rivers, such as at the Carolina Power and Light Company's Sutton Plant and along the Northeast Cape Fear River below Castle Hayne. Care must be exercised, however to prevent infiltration from the rivers where they contain brackish water. Brackish water extends upstream in the Cape Fear River as much as 10 miles above Wilmington during periods of low flow. This fluctuation in quality of water from time to time requires careful planning of ground-water development near the river.

Elsewhere the specific capacity of a properly designed and developed well generally is found to be at least 3 gpm per foot of drawdown throughout the county (fig. 19). Minimum yields of 150 to 250 gpm of potable water may be developed almost anywhere in the county.

The specific capacity of wells in the watershed of Smiths Creek north of Wilmington is greater than 20 gpm per foot of drawdown. Here, the sandstone aquifer, containing some calcareous material, has undergone solution and channels (fig. 19) in its upper surface contain up to 30 feet of coarse sand. Solution in the aquifer may account in part for the abnormally high specific capacity of well 112. Wells having exceptionally high specific capacities also are found in the limestone aquifer at Porters Neck (well 82) and near Wrightsville Beach (well 251). However, high specific capacities of wells in the limestone is much more sporadic than in the other aquifers.

The prohibitive cost of drilling test wells and the limited time available made it necessary to collect most of the data from existing privately owned wells. Thus, the available hydrologic data from remote and unpopulated areas are less than desired. Specifically, the position of the salt-water interface and information on the water-bearing characteristics of the sandstone aquifer are unavailable in the southern tip of the county. In areas where the geology is known but the hydrologic data are deficient, the aquifer characteristics are estimated by projecting known data from similar geologic situations.

The information presented in this section does not preclude the necessity of drilling exploratory wells when the desired quality of water is critical or when the needed quantity of water approaches the limits indicated in this report.

WATER-LEVEL FLUCTUATIONS

Observation wells were established in the different aquifers during the initial phase of the study to measure changes in ground-water storage.

Despite heavy rains ground-water storage is least during June, July, and August when evapotranspiration demands are greatest, and again during December after the fall "drought." The water level is highest in late February and early March during the period when winter rains are heavy and vegetation is dormant. There is frequently a secondary peak in ground-water levels in September resulting from heavy rains.

LOW-FLOW DISCHARGE MEASUREMENTS

The low-flow discharge of streams, sometimes called the "base flow," is that streamflow which occurs during long periods of fair weather. This flow is derived entirely from ground-water discharge. In order to evaluate the amount of ground water discharging in New Hanover County, measurements were made of the low flow of Smiths, Prince George, and Todds Creeks, as well as the flow from Greenfield Lake. These creeks and the lake are important areas of ground-water discharge in New Hanover County and may represent significant sources of water supplies.

In October 1965 a low-flow recession recorder was placed in operation on Smiths Creek about 500 feet southwest of N. C. Highway 132. Data from this recorder were used to determine what part of the streamflow is supplied by ground water. The streamflow in Smiths Creek, water levels in well 141, and the precipitation at the New Hanover County Airport are shown for the period from October 1965 to March 1966 in figure 20.

Smiths Creek has a drainage area of 8.9 square miles upstream from the low-flow recession recorder. It is a rural, sparsely populated area of which two-thirds is forest-covered and one-third is agricultural. Large ground-water withdrawals are not known in the area.

Figure 20 illustrates the relationship between precipitation, ground-water levels, and streamflow variations. During the period from late October through December the total precipitation at the nearby New Hanover County Airport totaled only 2 inches. Although plant transpiration and evaporation were low, they utilized nearly all the precipitation, and very little ground water was added to storage. Thus, the water level in well 141 declined at the nearly uniform rate of 0.03 feet per day. The ground water discharge into Smiths Creek, as indicated by the nearly horizontal segments of streamflow graph during this period, was approximately 2 cfs (cubic feet per second).

During the period from early January through the middle of March, when evapotranspiration losses were still at a minimum, the increased precipitation resulted in a rise in the water level in well 141 at rates of about 0.06 to 0.03 feet per day. As the aquifers became saturated a decreasing amount of the available precipitation went into storage and the contribution to streamflow was correspondingly increased.

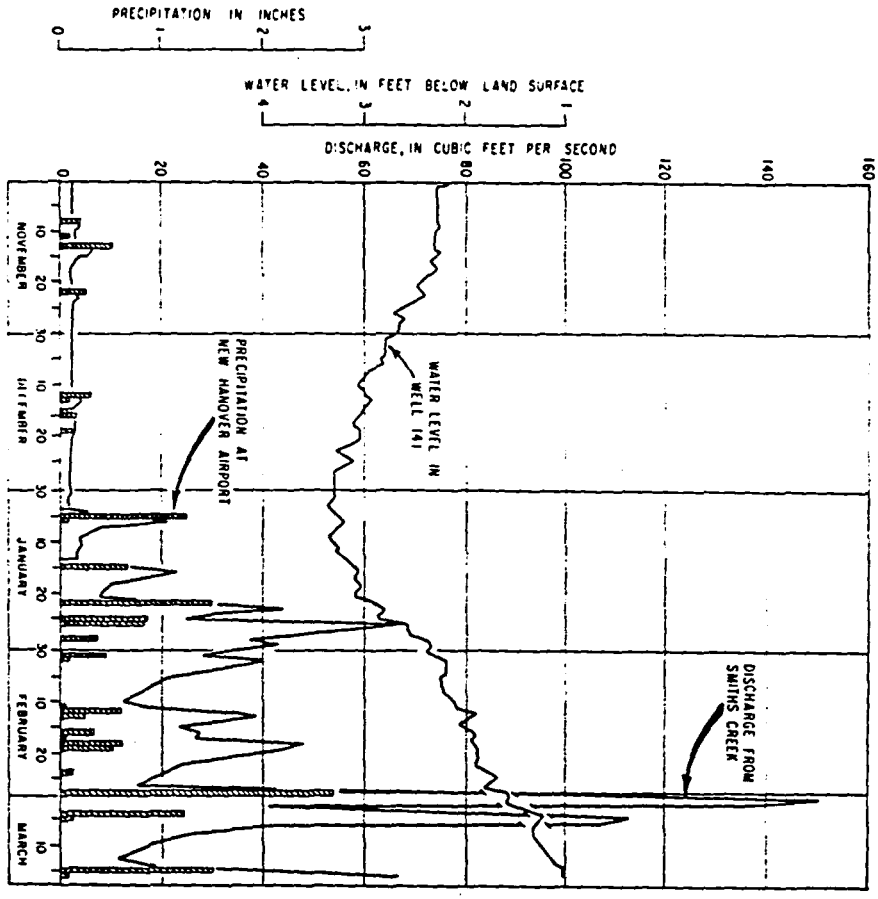

Figure 20.--Composite graph of precipitation at the New Hanover County Airport, discharge from Smiths Creek, and fluctuations of the water level in well 141.

On March 16 the water level in well 141 declined sharply possibly due to reduction of backwater effects in Smiths Creek combined with increased evapotranspiration. If it can be assumed that the evaporation losses and the precipitation from late October to January were similar to those from March 15 to April 25, then the 0.01 foot per day increase in the water-level decline in well 141 during that period can be attributed to plant transpiration.

The January 4, 1966, low-flow discharge of 1.8 cfs at the station on Smiths Creek represents about 1.2 mgd of ground-water effluent. The April 25, 1966, low flow of 1.6 cfs (1.07 mgd) is about 89 percent of its January rate.

Greenfield Lake is on the southern edge of the city of Wilmington. It has a drainage area of 4.1 square miles and was discharging 3.1 cfs (1.9 mgd) of water at the spillway on December 8, 1965. The streams draining into the lake are quite short, and their gradients range from 30 to 50 feet per mile. Thus the lake is in effect a very large spring. Although storm sewers drain into the lake, sanitary sewage lines do not.

Prince George Creek has a drainage area of 2.4 square miles above its intersection with the Blue Clay Road (rural road no. 1318). Most of the area is forest land. The December 9, 1965, discharge of 0.22 cfs represents 0.14 mgd of ground-water discharge.

Todds Creek has a forest drainage area of 0.03 square miles above its intersection with N. C. Highway 132. The December 9, 1965, discharge was 0.11 cfs (0.07 mgd).

QUALITY OF WATER

The quality of ground water in New Hanover County is influenced by the chemical and physical character of the water as it enters the ground and by the composition of the rocks through which it moves. Rainwater usually contains dissolved gases, chiefly oxygen and carbon dioxide, that make it slightly acidic and thus capable of dissolving mineral matter from the rocks comprising the aquifers. The chemical quality of water varies considerably between areas of recharge and areas of discharge. Shallow ground water in the county has a low hardness where the Pleistocene and Miocene sediments are not composed of soluble carbonates. Because of the water's acidity and the high solubility of iron in acid water, iron is leached from minerals in the aquifer. As water moves through the aquifer toward the discharge areas it tends to increase in mineral content, chiefly because of the solution of calcareous cement.

DISSOLVED MINERAL CONSTITUENTS

Chemical compounds of calcium, iron, potassium, sodium, magnesium, and most other common metals make up most of the dissolved mineral matter in ground water. Chemical analyses of water sampled from various aquifers in New Hanover County are given in table 2; partial analyses are reported in table 5. Complete analyses were made to give adequate areal and chemical representation of the individual aquifers. The sampling sites were chosen on the basis of data obtained from partial analyses.

The chemical analyses in this report are expressed in milligrams per liter (mg/l). As of October 1, 1967, the U. S. Geological Survey reports results of chemical analyses in milligrams per liter (mg/l) instead of in parts per million (ppm). In the fresh through moderately saline water range, mg/l are virtually equal to ppm. The following discussion gives pertinent information concerning the geologic source of dissolved mineral constituents, the recommended limits of the U. S. Public Health Service, methods of treatment, and their significance in relation to use.

SPECIFIC CONDUCTANCE

Specific conductance is a measure of the capacity of water to conduct an electric current. The conductance is primarily dependent upon the amount of dissolved constituents and their degree of ionization. Therefore, specific conductance values may be used to estimate the total amount of solids in solution. They are expressed in reciprocal ohms times 10^6 (micromhos) at a standard temperature of 25°C.

HYDROGEN-ION CONCENTRATION (pH)

The hydrogen-ion concentration, expressed in pH units, is the degree of acidity or alkalinity of the water. The pH of a solution is the negative logarithm of the concentration of the hydrogen ion in moles per liter. Numerically, the pH scale extends from 0 to 14. A water having a pH value of 7 is said to be neutral, and the concentration of hydrogen ions is equal to the

Table 2.--Chemical analyses of water

(Results in milligrams per liter except as indicated)

Well Number	Date of collection	Sample Depth	Specific conductance (micromhos at 25°C)	pH	Temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Dissolved solids (calculated)	Hardness: Calcium, magnesium	Hardness: Noncarbonate	Color
22	09/22/65		360	6.9 a/	65	12	64	3.3	7.0	1.1	190	10	9.3	0.3	1.9	0.0	0.1	0.32	0.02	202	174	18	0
23	05/20/52		737	7.1	--	41	84	8.5	58 b/		305	2.4	84	.1	.7	.--	--	.92	.07	446	245	--	2
29	10/21/65		427	6.8 a/	65	24	83	2.1	8.0	1.4	264	.4	11	.2	.2	.16	.1	2.9	.08	261	217	0	10
34	09/27/65		400	6.8 a/	64	29	72	1.1	12	1.4	230	.4	16	.1	.3	.1	.1	2.7	.09	246	186	0	5
38	09/23/65		456	7.1 a/	66	26	87	3.8	7.8	2.3	282	.4	12	.2	.3	.0	.2	1.6	.10	279	233	2	5
50	09/27/65		242	7.5	65	12	45	1.3	4.2	.8	129	8.4	7.0	.2	.2	.3	.1	.64	.03	143	117	10	5
51	06/11/65		33	6.5	66	5.9	3.4	.2	1.8	.6	11	2.4	1.6	.0	.4	.00	.1	.03	.03	21	10	1	0
53	06/11/65		195	7.2	68	5.9	17	.7	18	2.2	52	8.6	27	.0	.4	.01	.1	.57	.03	106	45	20	5
68	09/24/65		511	6.6 a/	66	12	101	2.9	8.6	1.0	310	.8	16	.2	.6	.1	.2	2.0	.05	297	264	10	70
70	09/24/65		540	6.7 a/	68	28	103	4.4	11	1.3	327	2.6	19	.2	.4	.0	.1	4.9	.08	331	276	8	10
86	09/23/65		447	7.1 a/	66	15	77	5.3	13	1.8	267	.6	16	.2	.3	.0	.1	1.0	.00	260	214	0	5
87	08/02/65	599	26100	7.7	68	8.8	195	233	5350	200	406	546	8780	.5	.2	.0	.5	6.0	.10	15600	1450	1110	7
87	08/12/65	320	10480	7.9	68	9.8	67	84	2330	90	408	58	3350	.1	1.1	.0	.3	.61	.04	6700	512	177	4
87	08/06/65	220	331	7.5	--	--	19	1.6	40	--	75	--	47	--	--	--	--	--	.00	--	54	0	--
96	09/23/65		582	7.2 a/	68	--	89	5.8	--	--	322	--	36	--	--	--	--	2.8	.09	--	246	0	5
108	09/27/65		29	5.1 a/	67	4.5	1.8	.5	2.1	.5	6	3.2	4.4	.1	.5	.0	.0	.02	.02	21	6	2	0
111	06/10/65		31	6.9	68	4.1	3.0	.4	1.8	1.9	10	2.2	3.0	.0	.3	.00	.0	.08	.03	22	9	1	0
115	08/04/65		174	6.5	66	6.9	18	1.5	7.8	1.9	14	9.4	14	.1	40	.0	.0	.89	.07	107	52	40	4
131	05/16/65		325	8.2		17	35	9.1	19	2.4	164	3.8	27	.1	.3	.0	.0	.19	.03	195	126	0	2
134	09/23/65		452	7.5	64	18	81	3.6	12	1.6	265	.4	18	.2	.3	.1	.1	2.2	.08	265	218	0	5
147	09/27/65		465	6.8 a/	68	--	90	2.9	--	--	284	--	13	--	--	--	--	2.7	.13	--	236	4	8
154	10/21/65		603	7.2 a/	66	22	86	12	32	3.8	333	1.4	39	.3	.3	.03	.2	.02	.00	361	264	0	12
155	09/24/65		450	7.0 a/	66	10	70	4.3	15	1.2	184	10	38	.2	13	.2	.1	.02	.01	252	193	42	5
160	09/27/65		774	7.0	66	30	100	10	50	5.1	359	1.4	78	.4	.5	.0	.2	.03	.01	452	293	0	15
167	12/06/65		677	7.6	--	23	80	14	44	6.3	322	8.8	61	.4	.2	.07	.2	.02	.00	396	256	0	7
177	09/24/65		361	7.1 a/	68	20	49	12	8.6	5.0	210	.4	15	.4	.1	.0	.1	.02	.02	214	170	0	5
178	09/24/65		369	6.7 a/	65	10	71	1.4	6.6	.8	220	.6	12	.1	.3	.0	.1	.71	.04	211	164	3	5
209	06/10/64		502	7.8	--	16	52	4.6	44	4.8	178	15	58	.2	.2	.0	--	.42	--	283	150	4	--
230	09/12/61		390 c/	7.4	--	12	200	12	--	--	--	70	20	--	.0	.0	.8	1.8	--	312	212	--	10
249	10/14/65		337	7.1 a/	--	8.7	60	2.8	8.7	.6	190	1.2	15	.1	.3	.36	.2	.67	.03	191	161	4	8
253	04/20/65		590	7.9	66	18	54	12	58	8.4	226	8.2	87	.3	.2	.0	.0	.85	.01	357	184	0	5
255	04/20/65		730	7.9	64	18	60	13	63	6.6	234	9.2	107	.3	.3	.0	.1	.85	.00	393	203	11	9
256	04/20/65		840	8.0	64	18	20	38	85	8.8	236	14	136	.3	.2	.0	.1	.32	.01	436	206	13	12
257	04/20/65		3050	8.0	64	18	69	64	392	22	228	86	800	.2	.1	.1	.2	.93	.00	1560	438	251	7
258	04/20/65		920	7.9	64	17	54	16	95	9.8	207	17	170	.4	.1	.1	.1	.43	.01	482	200	30	7
259	04/19/65		830	8.1	60	17	32	25	86	9.6	204	16	147	.4	.0	.0	.1	.09	.00	433	182	15	5

a/ Field pH meter value. b/ Calculated Na plus K, reported as Na. c/ Fulbright Laboratories, Inc.

Table 2.--Chemical analyses of water--Continued

(Results in milligrams per liter except as indicated

Well Number	Date of collection	Sampled Depth	Specific conductance (micromhos at 25°C)	pH	Temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Dissolved solids (calculated)	Hardness: Calcium, magnesium	Hardness: Noncarbonate	Color
260	04/20/65		980	7.8	56	17	60	19	100	9.3	223	16	187	0.4	0.1	0.0	0.0	2.5	0.02	519	226	44	7
262	04/21/65		671	7.6	--	17	56	12	67	8.9	222	9.6	109	.3	.2	.2	.1	1.9	.02	389	188	6	5
264	10/04/65		355	7.2 a/	--	--	61	4.2	--	--	204	--	16	--	--	--	--	2.0	.07	--	168	2	--
275	10/15/65		261	7.4 a/	--	--	48	2.3	--	--	152	--	11	--	--	--	--	.25	.02	--	128	4	--
281	10/20/65		260	7.3 a/	65	11	47	2.6	4.3	.8	154	1.4	7.0	.2	.1	.05	.2	.20	.01	151	128	2	10
287	09/30/65		195	7.4 a/	67	5.6	37	1.3	3.5	.5	110	7.2	7.6	.1	.1	.22	.2	.25	.15	117	98	8	8
288	09/29/65		218	7.7 a/	67	--	28	7.1	--	--	131	--	9.6	--	--	--	--	.06	.01	--	98	0	--
316	10/14/65		658	7.5 a/	--	18	50	17	64	6.8	260	2.6	90	.3	.2	.05	.2	.28	.01	377	196	0	14
317	10/14/65		598	7.5	--	30	55	22	32	2.4	237	1.0	72	.1	.3	.02	.1	1.3	.04	332	228	34	10
331	10/21/65		374	7.1 a/	66	3.1	72	2.3	5.9	.4	218	8.0	11	.2	.3	.24	.1	.05	.04	211	188	10	10
335	09/30/65		297	7.6 a/	67	--	31	6.1	--	--	126	--	62	--	--	--	--	.11	.02	--	102	0	--
340	09/30/65		426	6.8 a/	67	--	33	7.9	--	--	172	--	52	--	--	--	--	.14	.01	--	116	0	--
343	10/19/65		952	7.9 a/	67	12	31	12	142	12	147	12	219	.4	.1	.09	.1	1.4	.03	513	126	6	7
345	09/30/65		--	6.4 a/	65	--	48	1.6	--	--	151	--	16	--	--	--	--	4.0	.08	--	126	2	--
346	09/30/65		--	7.0 a/	68	--	72	6.0	--	--	245	--	13	--	--	--	--	6.3	.08	--	205	4	--
347	09/02/65	332	10500	6.8 a/	69	9.0	81	69	2000	70	365	545	2860	1.5	3.8	.01	.2	2.7	.05	5830	486	187	5
347	08/30/65	622	25300	7.3 a/	70	7.4	232	153	5110	.5	346	405	8310	1.1	1.9	.00	.4	15	.14	14600	1210	927	5
349	09/30/65		384	7.5 a/	66	18	35	13	25	4.8	178	2.0	38	.3	.2	.17	.2	.10	.02	225	142	0	12
362	10/16/65		552	7.3 a/	--	27	46	33	17	19	344	1.6	21	.5	.3	.10	.2	.81	.02	335	248	0	15
368	10/21/65		181	7.8 a/	69	--	33	.7	--	--	104	--	5.0	--	--	--	--	.26	.01	--	84	0	--
371	10/14/65		192	7.8 a/	--	9.1	35	1.8	3.7	.5	111	.8	6.9	.1	.2	.16	.2	.10	.01	114	94	3	10
372	09/30/65		324	7.3 a/	66	8.6	57	4.1	7.3	.7	190	1.4	12	.1	.2	.18	.2	.09	.03	185	158	3	15
381	10/26/65		271	7.5 a/	67	13	46	1.9	8.0	.6	152	1.6	12	.1	.2	.09	.0	1.3	.10	159	124	0	7
383	10/14/65		274	7.8 a/	--	12	35	7.8	10	1.4	144	2.4	15	.0	.2	.01	.1	.01	.01	155	118	0	1
388	10/14/65		374	7.4 a/	67	38	40	16	8.7	9.2	208	.6	22	.3	.1	.06	.1	.03	.01	237	168	0	11
390	10/21/65		129	6.8 a/	67	5.2	17	1.8	5.7	.9	50	5.2	10	.1	2.3	.05	.0	.14	.02	73	48	8	6
396	11/09/64		445	7.9	--	22	40	16	17	16	204	.6	37	.1	.1	.0	.1	.48	.00	249	166	0	10
397	11/10/64		522	8.0	--	27	39	24	22	18	243	.4	47	.1	.4	.0	.1	.96	.00	297	196	0	18
398	11/10/64		422	7.8	--	21	42	12	14	17	190	1.4	35	.1	.0	.0	.1	.25	.00	236	155	0	18
399	11/10/64		530	7.7	--	29	45	21	24	19	244	1.0	49	.1	.1	.0	.2	.22	.00	308	200	0	17
400	11/09/64		535	8.0	--	29	38	25	24	20	247	.2	50	.1	.0	.0	.2	.57	.00	308	200	0	7
405	10/22/64		675	7.8	67	43	87	13	28	17	354	.8	64	.2	1.1	.0	.3	.42	.00	428	274	0	25
406	10/19/65		490	7.5 a/	68	--	82	6.0	--	--	272	--	27	--	--	--	--	.60	.01	--	229	6	--
407	10/22/64		419	7.6	67	45	33	21	14	16	221	.4	34	.2	.3	.0	.1	.16	.00	273	170	0	10
409	02/07/63		397	7.7	--	40	30	22	6.6	17	207	.8	20	.2	.0	.0	.2	.13	.00	239	167	0	5
410	02/08/63		938	7.7	68	34	46	24	86	20	223	7.6	163	.2	1.1	.0	.2	.35	.00	493	215	32	5
411	02/08/63		419	7.6	66	32	65	3.6	15	1.8	205	4.0	26	.1	.0	.0	.1	.25	.03	249	178	10	5
412	10/11/65		1440	7.3 a/	68	22	60	16	197	18	195	1.6	360	.2	.3	.05	.2	.52	.02	771	217	57	10

a/ Field pH meter value.

concentration of hydroxyl ions. A water having a pH value greater than 7 is referred to as basic; that is, the concentration of hydroxyl ions exceeds the concentration of hydrogen ions. Conversely, if the pH is less than 7 the hydrogen ions exceed the concentration of hydroxyl ions and the water is said to be acidic. Inasmuch as the pH values are the numerical change to the logarithmic base, a water with a pH of 3 is ten times as acid as water with a pH of 4, and conversely a water with a pH of 9 is ten times as basic as a water with a pH of 8. The pH values are important indicators of the corrosive potential of ground water. Acid waters generally are more corrosive than alkaline waters.

The pH of ground water was determined by the author using a pH meter calibrated by standard buffer solution before each measurement. The water was pumped until its temperature stabilized, and then it was conducted by closed system to the pH cell. Most artesian water in the county had a field pH slightly greater than 7.0. The pH of waters that remained in sample bottles for several days ranged up to 8.2.

TEMPERATURE

The temperature of most water samples from New Hanover County ranged from 64 to 66°F. The average annual air temperature at the Wilmington weather station is 63.8°F for a 30-year period of record. Higher temperatures noted in table 2 were caused by warming of the water by the sampling pump or while in above-ground storage tanks. The higher temperatures of water from wells 87 and 347 are related to the relatively great depths to the aquifers at these wells.

SILICA (SiO_2)

Silica in ground water is derived from the weathering of silicate minerals that are common in the Coastal Plain materials. Except when present in high-pressure boiler feed or steam-turbine water, high concentrations of silica in ground water are not objectionable for most industrial processes. The concentrations of silica range from 4.1 to 45 mg/l and are highest in water from the limestone aquifer in New Hanover County.

CALCIUM (Ca) AND MAGNESIUM (Mg)

Compounds of calcium and magnesium are abundant in the limestones, marls, calcareous sands, and sandstones in the county and impart most of the hardness to the water. The ions of calcium and magnesium are similar in chemical reaction insofar as most water uses are concerned and are considered together in this report. Circulating acidic water dissolves calcium carbonate and carries it in solution as calcium bicarbonate. The quantity in solution is directly related to the carbon dioxide content of the water. The reaction is reversible so that where carbon dioxide is being released, such as at the screen and well head where there is a decrease in pressure, calcium carbonate is redeposited. In one well near Myrtle Grove, carbon dioxide (identified by chemical test) is occasionally released in sufficient quantities to cause cavitation of a 1/2-horsepower centrifugal pump.

The calcium and magnesium concentrations of well water in New Hanover County are given in table 2.

SODIUM (Na) AND POTASSIUM (K)

Concentrations of sodium and potassium in New Hanover County are low in ground water, except in wells 300 feet or more in depth, and in shallow wells near the coast. Along the sounds and beaches brackish water contains relatively high concentrations of sodium as well as chloride.

Water containing as much as 50 mg/l of sodium and potassium may be used for most domestic purposes; however, greater concentrations may cause foaming in high-pressure boilers. Sodium and potassium do not impart a noticeable taste to water in concentrations of less than several hundred milligrams per liter.

BICARBONATE (HCO_3 AND CARBONATE (CO_3)

Ground water in New Hanover County is principally the bicarbonate type with calcium and magnesium as the dominant cations. Where the chief cations are calcium and magnesium the water is usually hard. As demonstrated by water from well 87, the sodium ion is sometimes exchanged for the calcium and magnesium ions to produce a soft sodium bicarbonate water. This ion exchange principle is used in the zeolite softeners for domestic and industrial water supplies.

Bicarbonate has little effect on the domestic use of water, but it may cause foaming and scale formation in some industrial uses.

SULFATE (SO_4)

Sulfur-bearing minerals such as pyrite and marcasite are present in the sediments beneath the county. These minerals, and the calcium and magnesium sulfates frequently associated with shell and limestone beds, are soluble in ground water. Sulfate is also contributed to rainwater from airborne salt spray and industrial pollutants. Except in the deep test holes (wells 87 and 347), sulfate in water tested in the county did not exceed the U. S. Public Health Service recommended limit of 250 mg/l. However, sulfate may be reduced by bacteria and decaying organic matter to produce hydrogen sulfide and sulfur. The gas, hydrogen sulfide, a common nuisance in coastal counties, has an offensive rotten-egg odor; and when dissolved in water, forms a weak acid and imparts a characteristically disagreeable taste. The odor of these reduced waters can usually be remedied by chlorination to prevent bacterial growth. The effectiveness of both aeration and chlorination in the removal of H_2S is dependent upon the pH of the raw water.

CHLORIDE (Cl)

Small amounts of chloride are available from the decomposition of igneous rocks. However, the original source of most oceanic chloride is probably from volcanic gas and hot spring emanations associated with volcanic activity. More than 90 percent of the dissolved solids in the oceans are chloride salts, and the chloride ion concentration ranges from 19,000 to 20,000 mg/l in sea water. Chloride salts are incorporated within the porous sediments when they

are deposited or submerged beneath the ocean. Airborne salt spray also contributes chloride to the aquifers in coastal areas (Wait and Callahan, 1965). The rate of flushing of these aquifers by fresh water depends on time, the hydraulic head, and the composition of the flushing water.

Chloride concentrations are less than 40 mg/l in waters from the water-table aquifer. Chloride concentration is less than 20 mg/l in the limestone aquifer (fig. 18), except along the estuaries and sounds where it ranges from 50 to 400 mg/l due to lateral encroachment of brackish water. Encroachment of brackish water is a problem, especially where dredging of the Intracoastal Waterway along Middle Sound has breached the permeable Castle Hayne Limestone. Chloride concentration in the sandstone aquifer (fig. 15) is less than 50 mg/l everywhere within the interior of the county at depths of less than about 200 feet. Except in areas of heavy pumping, chloride concentrations in this aquifer along the sounds and at Wrightsville Beach range from 50 to 260 mg/l. No information is available from the southern end of the county where the sandstone aquifer lies below a depth of 200 feet. In test wells 87 and 347 the chloride content of the water is about 3,000 mg/l at a depth of 300 feet and more than 8,000 mg/l at a depth of 600 feet.

The U. S. Public Health Service recommends that the chloride content not exceed 250 mg/l in water used for domestic and public supplies. The chloride-contamination problem is further discussed in a following section.

FLUORIDE (F)

Fluoride in ground water is due to the solution of fluoride-bearing minerals such as apatite, fluorapatite, the phosphates, the micas, hornblende, and organic matter such as shells. The micas, phosphates, and shells are prevalent in the sediments of the county and probably contribute most of the fluoride in the ground water.

Fluoride in concentrations between 1.0 and 1.5 mg/l in drinking water aids in reducing tooth decay in children. In concentrations greater than 1.5 mg/l fluoride may cause permanent mottling of the teeth (dental fluorosis) when used by children (Maier, 1950, p. 1120-1132. Fluoride concentrations averaged 0.2 mg/l and ranged from 0 to 0.5 mg/l in all ground water tested in wells as much as 200 feet deep.

NITRATE (NO_3)

Nitrate in ground water is generally considered to be the final oxidation product of nitrogeneous (organic) waste. A nitrate concentration in excess of 3.0 mg/l generally would indicate a nearby source of pollution. Shallow dug wells and well points are most often subject to pollution from sewage, fertilizers, and polluted surface waters.

The so-called "blue-baby" condition is a possible hazard when water containing nitrate concentrations in excess of 45 mg/l is mixed in feeding formulas. Water from all but one of the wells tested in the county had nitrate concentrations less than the U. S. Public Health Service recommended maximum of 45 mg/l. Well 115, which draws water from beds of permeable sand, is probably contaminated by nitrogen fertilizers.

PHOSPHATE (PO_4)

Phosphate in ground water may result from the solution of apatite or phosphate fertilizers. Phosphate concentrations in ground water tested in New Hanover County were below 0.4 mg/l.

ALUMINUM (Al)

Aluminum is a very common element in the earth's crust. However, high concentrations of aluminum are not common in ground water because this metal is only slightly soluble in water under the conditions that prevail in New Hanover County. Aluminum concentrations in ground water tested were below 0.5 mg/l.

IRON (Fe) AND MANGANESE (Mn)

Iron in excess of 0.3 mg/l is objectionable for many uses. Excessive amounts of iron and manganese impart a reddish-brown color to utensils, plumbing fixtures, and laundry. It also interferes with dyeing and the manufacturing of some products, such as paper and photographic film.

Excessive iron concentrations are common in water in the shallow sediments in the county. The shallow ground water generally is more corrosive than deeper water. Oxygen and carbon dioxide are the principal constituents of ground water causing corrosion. As the shallow water moves downward through the soil and other sediments, the oxygen is used up in the oxidation of organic and inorganic matter; the carbon dioxide reacts with carbonates to form bicarbonates.

it is not always apparent whether the iron is in the water as it enters the well, or whether it is dissolved from the well casing and pipes. It is important to determine the source of the iron, whether dissolved from the rocks or the pipes, before methods for its removal are employed.

Iron concentrations in the water sampled are generally more than 1 mg/l from wells in the water-table aquifer, between 0.3 and 4.0 mg/l for water from the limestone aquifer, and less than 0.3 mg/l in the sandstone aquifer in areas along the Atlantic coast and the Cape Fear and the Northeast Cape Fear Rivers.

The chemical behavior of manganese in water resembles that of iron. However, since manganese is much less abundant in rocks, its concentrations in ground water are generally lower than iron concentrations. The U. S. Public Health Service recommends that manganese not exceed 0.05 mg/l in drinking and cooking water. Ninety-one percent of the water samples analyzed for manganese contained less than 0.05 mg/l. Manganese ranged from 0.0 to 1.5 mg/l in ground water in New Hanover County.

DISSOLVED SOLIDS

Total dissolved solids are the residue after a given volume of water has been evaporated and dried at a definite temperature (180°C by the U. S. Geological Survey methods). Computed dissolved solids are equal to approximately one-half the bicarbonate plus the sum of the other chemical constituents in milligrams per liter. Computed dissolved solids are used in the report, unless stated otherwise.

The U. S. Public Health Service recommends that dissolved solids in public water supplies not exceed 500 mg/l. Except in cases of chloride contamination, dissolved solids are less than 500 mg/l in ground water in New Hanover County.

HARDNESS

Hardness of water is usually recognized by the increased amount of soap necessary to form and maintain a lather. Hard water is objectionable not only because of its soap-consuming properties, but also because it forms scale in boilers and, to a lesser degree, encrustations in cooking utensils. The principal ions that produce hardness in ground water are calcium and magnesium, which have been discussed in a previous section. The following classification of water hardness is used by the U. S. Geological Survey.

Hardness as $CaCO_3$ (mg/l)	Classification
0 - 60	Soft water
61 - 120	Moderately hard water
121 - 200	Hard water
More than 200	Very hard water

Figure 14 shows the areal distribution of the hardness in the sandstone aquifer. Most of the water in the county with the exception of that from the water-table aquifer would be classed as hard to very hard water of the calcium-bicarbonate type.

Hardness in excess of that equivalent to the carbonate and bicarbonate present in the water is referred to as noncarbonate hardness.

OCCURRENCE OF SALTY WATER AND ITS POSSIBLE ENCROACHMENT

In New Hanover County it is important to know where the salty water occurs in the ground as well as in the major rivers so that fresh water can be developed without encroachment of salty water. The county is underlain by aquifers containing brackish to highly saline sea water. The overlying reservoir of fresh water exists in dynamic equilibrium with the underlying and surrounding salt water.

The contact between fresh water and the underlying salt water lies within the Peedee Formation everywhere in the county except in the limestone near the sound at Porters Neck. The upper part of the Peedee contains fresh water. The data from several deep wells indicate that saline water progressively increases in chloride concentration to basement. Figure 6 shows the general configuration of the top of a sand bed in the Peedee Formation that contains more than 3,000 mg/l chloride, and indicates that the top ranges from about 180 feet below mean sea level in the western part of the county to about 340 feet below sea level in the eastern part.

The chloride and other pertinent data from two deep test wells drilled during this investigation and the available data from all previously known exploratory wells are summarized below in table 3.

Table 3.--Summary of deep test well data

Name	Date Drilled	Well No.	Depth of sample below msl (ft)	Formation	Elevation of land surface (ft)	Water level above sea level (ft)	Chloride (mg/l)	Temperature (°F)	pH	Remarks
Olsen, near Murraysville	1965	87	278 557	Peedee Peedee	32	18 -40	3,350 8,750	67.5 69		
Edwards, about 2 miles NW of Myrtle Grove	1965	347	300 596	Peedee Peedee	22	12 -40	2,960 3,311	68.9 70	6.8 7.3	
Wrightsville Beach	1953	261	235 350	Peedee Peedee	5		650 1,000+			Brown, 1958a
Allied Kennecot		342	29+	Peedee	17					Brackish water reported
Carolina Power & Light		Near 128	380	Peedee	8					Brackish water reported
Swart Dairy		97	335	Peedee	35	28	3,000 approx.			
Fort Caswell	1903		1,540	Tuscaloosa			8,000+	89		Salty from 365 to 1,540
Carolina Trucking Development Co.	1905	Near #15	250-318 318-350	Peedee Peedee	20 20	Nonflowing Flowing				Reported salty, Clark and others, 1912

Saline waters from these aquifers are possible sources of bromine and other rare salts. Too, the chloride-total hardness ratios in these waters are such that they possibly may be used to regenerate sodium cation water softeners. With suitable noncorrosive plumbing, their high temperatures could be employed for heating. There is a possibility that these aquifers could be used for disposal of industrial wastes.

Ocean water lies everywhere off the county's eastern shore and moves with the tides up and down the Cape Fear and Northeast Cape Fear Rivers and most of the larger creeks. The distance traveled depends upon the volume of downstream flow and the height of the tides. The denser sea water moves wedge-like along the stream bottom, and the fresh water flows out above it; however, turbulence causes some mixing along the salt-water interface. Where

infiltration occurs, the quality of water from wells located near the ocean and river estuaries is dependent on the salt content of the water that infiltrates and the proportion it represents of the water pumped.

The position of the salt-water interface beneath New Hanover County depends upon the height of the fresh water above sea level and the density of the sea water. Due to the difference in density between fresh water and salt water, fresh water floats upon salt water much as oil does upon water in accordance with Archimedes' principle. In a small land body composed of homogeneous sand and surrounded by water a reduction in the fresh water level of one foot will theoretically cause a corresponding rise in the underlying sea water of 40 feet. Although exact conformance with the above principle does not occur in New Hanover County or in most coastal aquifers due to diffusion or mixing along the salt-water interface (fig. 21) (Kohout, 1961, and Cooper and others, 1964) variation in vertical and horizontal aquifer permeabilities, and incomplete encirclement of the county by sea water, a small decrease in the height of the fresh water above sea level may result in a much larger upward movement of the salt-water interface. Thus, a reduction in rainfall or an increase in the withdrawal of water by pumping, swamp drainage, or dredging reduces the hydrostatic head and results in a corresponding encroachment of the salt water.

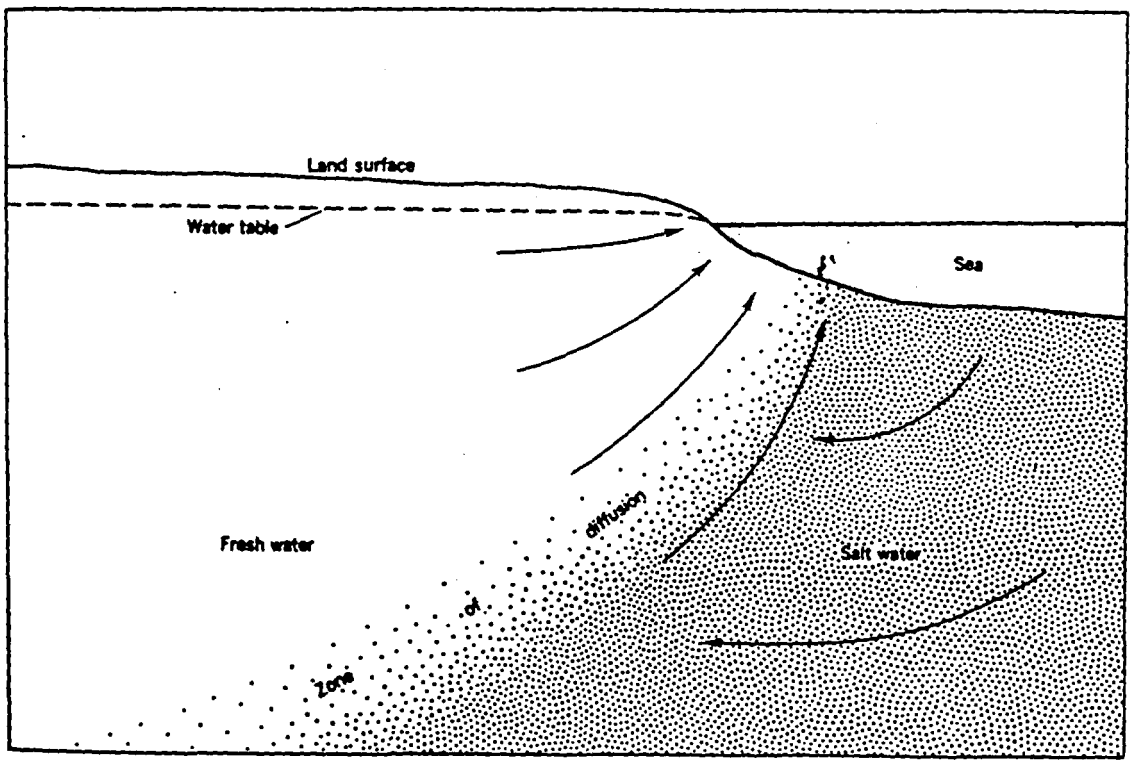

Figure 21.--Diagram showing the circulation of salt water and fresh water in a coastal aquifer. (Include credit in title).

Figures 15 and 18 show that the chloride concentrations are greater in the vicinity of creeks, sounds, and estuaries where the hydrostatic head approaches zero. This is shown also at Kure, Carolina, and Wrightsville Beaches where the hydrostatic head has been lowered by pumping. The result has been a slight upward movement of salt water or lateral movement of sea water from the ocean and estuary, or both. Where lateral encroachment of saline water occurs in the shallow aquifers, such as along the Cape Fear River and the sound at Porters Neck, entrance of salt water to the well may be prevented by extending the well casing through the contaminated zones and deriving water from the fresh zones below. Vertical encroachment can be controlled by well-field design and management practices that decrease the drawdown of the water level and spread the cones of depression over a wider area. Proper practices include pumping more wells at lower rates and using multiple well points and infiltration galleries for shallow installations.

Although chloride contamination is not a serious problem in New Hanover County, the fact that it can happen is borne out by the increased chloride content of the Wilmington wells pumped at high rates during the drought of 1940, and by the recent increase of chloride in wells 342 and 257.

Data are insufficient for making quantitative determinations of safe yields for wells in the several aquifers at any specific point in the county. In areas of heavy pumping it is advisable to monitor the chloride content of the water at the point of pumping and in surrounding observation wells. This method is being used by the Superior Stone Company for advanced warning of contamination.

The quality of ground water near the rivers may be influenced by the quality of the river water. Chloride concentrations and other chemical data collected by the U. S. Geological Survey on the Cape Fear and Northeast Cape Fear Rivers are given in Bulletin 1, volume 7, of the North Carolina Department of Water Resources (Woodard and Phibbs, 1965). A typical chemical analysis of sea water is given in table 4 for those constituents that occur in excess of 1 mg/l.

Table 4.--The composition of sea water

Constituent	Concentration (mg/l)
Chloride (Cl)	18,980
Sodium (Na)	10,560
Sulfate (SO_4)	2,560
Magnesium (Mg)	1,272
Calcium (Ca)	400
Potassium (K)	380
Bicarbonate (HCO_3)	142
Bromide (Br)	65
Strontium (Sr)	13
Boron (B)	4.6
Fluoride (F)	1.4

(Adapted from Rankama and Sahama as given in Hem, 1959.)

WELLS AND WELL CONSTRUCTION

Existing privately owned wells and test wells drilled for or by the U. S. Geological Survey were the source of most of the data used in this report. Data for these wells are given in table 5 at the end of the report. The 412 wells inventoried are numbered horizontally across the map of the county and are shown in figure 3.

The well data indicate that problems encountered in obtaining adequate supplies of well water of good chemical quality may result from inadequate well construction. Wells frequently have a low specific capacity because of poor construction or development methods, and they may produce water of undesirable chemical quality because they tap the least desirable of several aquifers. The following section on well construction, adapted in part from Wyrick (1966) is included to help minimize some of the problems by improved well design.

Water-well construction is usually governed by the owner's water needs and the cost of the well. As the owner must determine what his requirements are, the following discussion describes the various methods of well construction and the advantages and disadvantages of each. The types of wells constructed in New Hanover County are shown in figure 22. These wells fall into three categories; bored wells, driven wells, and drilled wells. In figure 22 diagram A is a large dug well, the next one (B) is a driven well, and the others shown are drilled wells.

Where large quantities of water are needed for irrigation, ponds are frequently dug and used as wells. The chemical quality of the water is comparable to that from shallow driven wells. Infiltration galleries and multiple well-point installations also may be constructed where domestic needs preclude the use of open ponds or where caving is a problem.

Driven wells are constructed by driving a length of steel well casing with a pointed drive-screen into a sandy water-bearing zone. The well is developed to clear the finer sandy material from the screen area and then equipped with a pump. Driven wells in New Hanover County are usually 1-1/4- to 2-inches in diameter and less than 30 feet in depth.

Several types of drilled wells are constructed in New Hanover County. Among these types are: open-end wells, single- or multiple-screened natural-development wells, and the single- or multiple-screened gravel-pack wells. Multiple-screen wells may also be naturally developed, but none of this type were found in the county.

Well C in figure 22 illustrates the open-hole type of well. This type is constructed by drilling into consolidated rock, such as the Castle Hayne Limestone, and setting a steel casing in the top of the consolidated rock. Usually the well is then deepened to the sandstone aquifer of the Peedee Formation and cleaned by pumping. This type of construction is restricted to areas which are underlain by materials sufficiently consolidated to insure

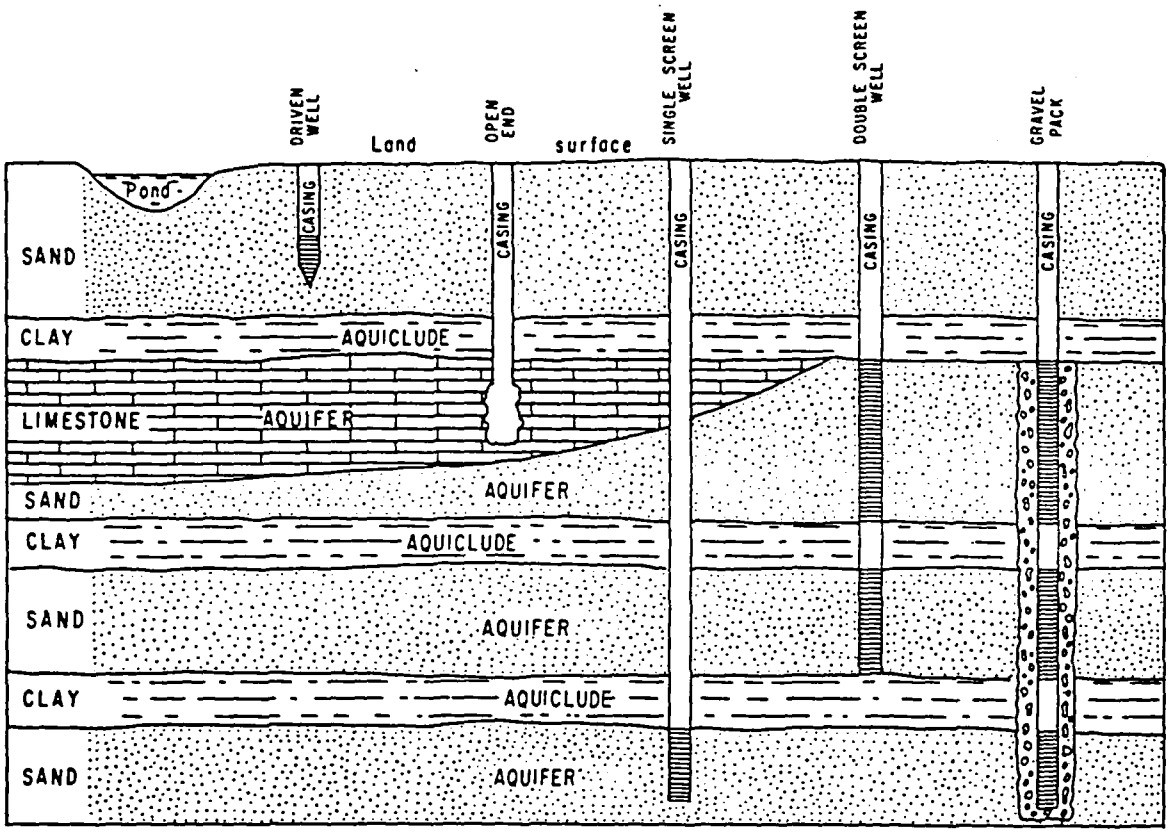

Figure 22.--Diagram showing types of wells constructed in New Hanover County.

that the hole will remain open below the bottom of the casing. This is the most common type of construction for domestic wells in the county.

The screened naturally developed well is illustrated by diagram D in figure 22. This type of well is constructed by drilling into a sandy aquifer and setting a steel casing with one or more screens on the lower end so that the screens are in the sandy aquifers. The well is developed by washing fine sand and clay particles from the aquifer around the screen. In this method of construction it is important that the screen openings be large enough to allow about 50 to 70 percent of the fine sand in the aquifer to wash into the well. In developing the well by pumping and surging, the fine material of the aquifer is washed out of the well and the nearby formation, leaving coarse, more permeable material packed around the screen. Common problems in this type of well construction usually include (1) poor well development due to improper screen size or insufficient surging and pumping, and (2) setting the screen so that part of the screen openings are blocked by clay layers.

Screened gravel-packed wells are illustrated by diagrams E and F in figure 22. This type of well is constructed by drilling a hole through one or several aquifers, reaming or washing a large diameter hole in each aquifer to be screened, setting a casing with screens spaced in the casing at each reamed

aquifer, pumping gravel into the large diameter holes outside of the screens, and developing the well to remove drilling clay and fine material from the gravel zones. The gravel packing effectively increases the radius of the well in each aquifer. This, in turn, increases the specific capacity of the well. Generally, only municipal or industrial wells are constructed in this manner because of the greater cost.

CONCLUSIONS

New Hanover County is underlain by sediments ranging in age from Cretaceous to Holocene. These sediments occur in layers most of which tend to slope at low angles toward the Atlantic coast. They are composed of sands, clays, and limestone, and lie on a floor of hard consolidated rocks at a depth greater than 1,000 feet. A very large volume of water is stored in the sediments of the Coastal Plain, but sediments below depths of approximately 300 feet contain water that is too salty for normal use.

The usable ground water in the county occurs in three major aquifers. The uppermost aquifer is that of the surface sands, of Miocene and Pleistocene age, that extend over the county. This aquifer is especially important along the western edge of the county where sand dunes overlie coarse sand of Pleistocene(?) age. This aquifer is replenished by precipitation directly, and the water table is near land surface in much of the county. Water from this aquifer discharges into streams and into low swampy areas and into the underlying aquifers. Many shallow well points obtain water easily from this aquifer. The water is low in mineral matter but tends to be corrosive.

Below the surface sand in the eastern, central, and northern parts of the county is the Castle Hayne Limestone of Eocene age. This limestone is in most places less than 40 feet thick. It yields as much as 600 gallons per minute to a few wells, 150 to most, and is considered a good aquifer. Specific capacities of existing wells range from 3 to 60 gpm per foot of drawdown. The water is of the calcium bicarbonate type, being moderately hard to very hard in quality.

Underlying the Castle Hayne Limestone and separated from it by some relatively impermeable clays is the sandstone aquifer in the Peedee Formation. It yields 200 gpm to many wells and in excess of 400 to some; in most places it is used in conjunction with the Castle Hayne Limestone aquifer. Specific capacities range from one to 75 gpm per foot of drawdown.

Although each of the aquifers is to a great degree a separate unit, the less permeable materials between the aquifers allow some interchange of water. Heavy withdrawals from either the Castle Hayne or the Peedee sandstone aquifers will tend to affect movement of water to or from the other.

The development of ground water on a large scale in New Hanover County should be considered with care because of the possibility of encroachment of salty water into the fresh-water beds. This encroachment may occur vertically upward from beds containing salty water. Near the coast and along the Cape Fear and Northeast Cape Fear Rivers lateral encroachment of brackish water or sea water into the fresh-water formations is possible when the water level is drawn down appreciably by pumping.

If heavy withdrawal is contemplated the following considerations may prove helpful:

1. A more detailed investigation of the local hydrologic conditions is needed to determine the positions and character of impermeable beds that could prevent or retard encroachment.

2. Periodic determinations of chloride in water from one or more observation wells that yield water from an area between the producing wells and the salt-water body, would be helpful in detecting increase in chloride content. This would give sufficient warning so that the rate of pumping could be decreased and an orderly evaluation of the water problem could be made.

3. Properly spaced producing wells would prevent excessive drawdown at the apex of the cone of depression.

4. The draining of swamps in recharge areas would lower the water table and have other effects upon the ground-water reservoir.

5. Capping flowing wells in the county would help to preserve the hydrostatic head necessary to prevent salt-water encroachment.

6. Introduction of contaminants into the aquifer would pollute the water supply.

7. Long-lived radioactive waste would make the water unsafe for generations. Plugging all abandoned salt-water wells with clay or concrete (from the bottom up) would prevent the contamination of fresh-water aquifers in the event that corrosion causes eventual rupture of the well casing.

So long as care is taken to prevent the encroachment of salty water into the fresh-water aquifers, a fuller use of the ground-water resources can be made. The county has not yet approached an optimum development of its ground-water resources.

REFERENCES

Brown, P. M., 1958a, Well logs from the Coastal Plain of North Carolina: North Carolina Dept. Conserv. and Devel. Bull. 72, 68 p.

_____ 1958b, The relation of phosphorites to ground water in Beaufort County, North Carolina: Econ. Geology, v. 53, p. 85-101.

Clark, W. B., Miller, B. L., Stephenson, L. W., Johnson, B. L., and Parker, H. N., 1912, The Coastal Plain of North Carolina: North Carolina Geol. and Econ. Survey, v. 3, 540 p.

Cooke, C. W., 1931, Seven coastal terraces in the southeastern states: Jour. Wash. Acad. Sci., v. 21, p. 503-513.

Cooper, H. H., Jr., Kohout, F. A., Henry, H. R., and Glover, R. E., 1964, Sea water in coastal aquifers: U. S. Geol. Survey Water-Supply Paper 1613-C, 84 p.

DuBar, J. R., and Johnson, H. S., Jr., 1964, Pleistocene "Coquina" at 20th Avenue South Myrtle Beach, South Carolina, and other similar deposits: Southeastern Geol., v. 5, no. 2, p. 79-99.

Gibson, T. G., 1967, Stratigraphy and paleoenvironment of the phosphatic Miocene strata of North Carolina: Geol. Soc. America Bull., v. 78, p. 631-650.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U. S. Geol. Survey Water-Supply Paper 1473, 269 p.

Kimrey, J. O., 1964, The Pungo River Formation, a new name for middle Miocene phosphorites in Beaufort County, North Carolina: Southeastern Geol., v. 5, no. 4, p. 195-205.

Kohout, F. A., 1961, Case history of salt water encroachment caused by a storm sewer in Miami: Am. Water Works Assoc. Jour., v. 53, no. 11, p. 1406-1416.

LeGrand, H. E., 1960, Geology and ground-water resources of Wilmington-New Bern area, North Carolina: North Carolina Div. Water Res. and Eng. Bull. 1, 80 p.

LeGrand, H. E., and Brown, P. M., 1955, Guidebook of excursion in the Coastal Plain of North Carolina, Oct. 8-9: Carolina Geol. Soc., published by North Carolina Div. Mineral Resources, Spec. Pub., 43 p.

Maier, F. J., 1950, Fluoridation of public water supplies: Am. Water Works Assoc. Jour., v. 42, pt. 1, p. 1120-1132.

Mundorff, M. J., 1945, Progress report on ground water in North Carolina: North Carolina Dept. Conserv. and Devel. Bull. 47, 78 p.

Thompson, D. G., 1941, Preliminary conclusions in regard to ground water for public supply at Wilmington, North Carolina: U. S. Geol. Survey open-file report.

U. S. Bureau of the Census, 1960 Statistics for North Carolina by counties.

U. S. Dept. of Commerce, 1962, Decennial census of United States climate--Monthly normals of temperature, precipitation, and heating degree days, North Carolina: Washington, U. S. Govt. Printing Office, 3 p.

_____ 1963-66, Climatological Data--North Carolina: Asheville, North Carolina.

U. S. Dept. of Health, Education and Welfare, 1962, Public Health Service Drinking Water Standards: Washington, U. S. Govt. Printing Office, 61 p.

Woodard, T. H., and Phibbs, E. J., Jr., 1965, Chemical and physical character of surface waters of North Carolina, 1962-63: North Carolina Dept. Water Resources Bull. 1, v. 7, 206 p.

Wyrick, G. G., 1966, Ground-water resources of Martin County, North Carolina: North Carolina Div. Ground Water Bull., no. 9, 85 p.

Table 5.--Records of wells in New Hanover County, N. C.

Ownership: C-County; F-Federal Government; M-Municipal; N-Corporation or Company; P-Private; S-State agency; Use: A-Air Conditioning; C-Commercial; H-Domestic; I-Irrigation; N-Industrial; P-Public supply; S-Stock supply; T-Institutional; U-Unused. Type of QW analysis available: P-Partial; C-Complete. Log data available: D-Driller's log; E-Electric log; G-Geologist log; J-Gamma-ray log. Well finish: G-Gravel with screen; S-Screen; T-Sand point; X-Open hole. Quality of water: Iron, pH, Chloride, Hardness, and Specific conductance are coded according to range in concentration. Explanation of code given on last page of tables. Aquifer: Kpd-Peedee; Tch-Castle Hayne; TQ-Undifferentiated late Tertiary and Quaternary sands

Well No.	Well location		Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water					Water-bearing unit	Remarks
	Lat	Long															Iron	pH	Cl	Hardness	Sp. Cond.		
1	342216N	0775403	1	USGS	F	U	P	G	29	30	2	T	5				5	7	1	4	2	Kpd	Temp. 65°F.
2	342205N	0775154	1	SUPERIOR STONE	N	U		J	50		2	X	5	5					2			Tch	
3	342147N	0775145	1	LEWIS NIXON	P	H	P		60		1	X	25	23								Tch	
4	342239N	0775048	1	IDEAL CEMENT	N	N	C	D	160	23	24	G		15	322	30						Tch-Kpd	
5	342225N	0775049	1	IDEAL CEMENT	N	N	C	D	164		24	G	27	19	325	20						Tch-Kpd	
6	342222N	0775045	1	IDEAL CEMENT	N	U			75		7	X										Tch-Kpd	obs. well
7	342211N	0775051	1	IDEAL CEMENT	N	N	C	D	160		24	G		18	329	29						Tch-Kpd	
8	342209N	0774930	1	HARLEY SMITH	P	H			40		1	X	23	7			7		0	5	3	Tch	
9	342130N	0775008	1	J B WILCOX	P	I	P	J	117	54	6	X	26	29	125		8		0	6	3	Tch-Kpd	
10	342115N	0775309	1	E NIXON	P	H			50	21	2	X	24	12								Tch-Kpd	
11	342112N	0775306	1	W A PENDER SR	P	H			35		1	X	23	12								Tch-Kpd	
12	342111N	0775329	1	NEGRO BAPT CH	P	T			26		1	X	23	10								Tch	
13	342133N	0775353	1	QUEEN TIRE SER	P	C			50	30	2	X	19	9	90		2		1	6	3	Kpd	
14	342116N	0775402	1	RAINBOW END MOT	P	C			50	36	2	X	19	11			3		1	6	3	Kpd	
15	342123N	0775414	1	JOHN LOREK	P	I			30	12	3	X	13	8	80							Tch-Kpd	
16	342127N	0775427	1	JOHN LOREK	P	I	P		21		4	X	14	8	100		5		1	6	4	Tch-Kpd	
17	342129N	0775418	1	JOHN LOREK	P	H			18		1	X										Tch-Kpd	
18	342051N	0775520	1	W H JONES	P	H			37		2	X	15	7			2		0	5	2	Kpd	

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
19	342045N	0775404	1	SMITH BARBER	P	H	P		40		1	X					6		0	6	3	Kpd	
20	342043N	0775402	1	MELLO ICE CREAM	N	C	P		10		30	X					0	7	0	5	3		Spring flow 10 gpm
21	342030N	0775427	1	ST STANISLAUS	P	T	P		180		2	X					4		0	5	3	Kpd	
22	342033N	0775413	1	WILM PACKING	N	C	C		68		4	X	18		80'		3	6'	1	5	3	Kpd	
23	342033N	0775409	1	WILM PACKING	N	A	C		21		6	X	*15	9			4		2	6	4	Tch	
24	342033N	0775326	1	REASOR CHEMICAL	N	N		DJ	150	30	10	G	22	9	400	75			2			Tch-Kpd	3 screens between 30'-120'
25	342045N	0775336	1	REASOR CHEMICAL	N	N		D	148	34	10	G		8	300	20						Tch-Kpd	Screened 33'-148'
26	342034N	0775323	1	REASOR CHEMICAL	N	U		D	212	14	6	X	22	11								Tch-Kpd	Stratigraphic test
27	342035N	0775324	1	REASOR CHEMICAL	N	N		D	150	33	6	G		4	200	12	5		2	6	4	Tch-Kpd	Screened 3[illegible]'-133'
28	342025N	0775245	1	HENRY BAND	P	I			69	26	2	X	16	1			6		2	4	3	Tch-Kpd	
29	342028N	0775216	1	R D TARDUGNO	P	H	C	G	60	20	2	X	29	11	*30		5	6'	1	6	3	Tch-Kpd	Temp. 65°F
30	342043N	0775207	1	A H PARKER	P	H			60	20	2	X	29		*40		7		1	6	4	Tch-Kpd	
31	342012N	0774925	1	USGS	F	U		J	94	92	1	T	33	7								Kpd	Auger hole No. 6
32	342012N	0774925	2	USGS	F	U		J	42	40	1	T	33	4								Tch	Auger hole No 6
33	342036N	0774755	1	USGS	F	U		J	75	73	1	T	22	0								Kpd	Auger hole No 45
34	342019N	0774727	1	JOSEPH WENEUT	P	H	C		42		2	X	40	9			5	6'	1	5	3	Tch	Temp. 66°F.
35	341948N	0775147	1	C LITTLEJOHN JR	P	H			50		2	X					5		0	5	3	Tch	Much iron reported
36	341933N	0775205	1	RAEFORD TRASK	P	I			87		6	X	39	12								Kpd	
37	341934N	0775253	1	ARTHUR KAUFMAN	P	U			29		1	X	28	4								Tch	
38	341954N	0775316	1	K E KORNEGAY	P	H	C		58	52	2	X					5	7'	1	6	3	Kpd	
39	341959N	0775312	1	MR HILL	P	H			52	24	2	X		9	*100							Tch-Kpd	
40	342015N	0775323	1	H A BRANCH JR	P	H	P		40		2	X					5		1	6	3		
41	342001N	0775431	1	S C STRICKLAND	P	U	P		24		1	X	21	7			7					Tch	
42	342003N	0775434	1	S C STRICKLAND	P	H			90	81	2	X	21	6	45							Kpd	

* Estimated. ' pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location		Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water					Water-bearing unit	Remarks
	Lat	Long															Iron	pH	Cl	Hardness	Sp. Cond.		
43	342010N	0775441	1	J W SAVAGE	P	H	P		44		2	X	*21	5	*60		6		1	4	2	Tch-Kpd	
44	342017N	0775436	1	J S CAMERON	P	U			40		4	X		8								Kpd	
45	342018N	0775441	1	J S CAMERON	P	U			179		4	X		8			3	7	5			Kpd	
46	342018N	0775445	1	J S CAMERON	P	H			55		1	X					3	7	1	6		Kpd	
47	342007N	0775504	1	HUGH OOSTERWYK	P	I			71		3	X	21	6								Kpd	
48	342000N	0775524	1	HUGH OOSTERWYK	P	I	P		74		8	X	21				5		2	6	4	Kpd	
49	341936N	0775527	1	S J SZCZERBIAK	P	H			100		1	X	25	1			4		2	6	3	Kpd	
50	341926N	0775658	1	USGS	F	U	C	GJ	54	52	2	T	34				4	7[1]	0	4	2	Kpd	Obs [illegible]
51	341928N	0775939	1	USGS	F	U	C	GJ	48	46	1	T	18	15			0		0	0	0	TQ	Obs [illegible]
52	341957N	0775957	1	USGS	F	U		J	38	36	2	T	7									TQ	
53	341932N	0780127	1	USGS	F	U	C	G	20	18	2	T	3	1									Aq[illegible]
54	341832N	0775904	1	USGS	F	U		GJ	65	62	2	T	17									TQ	
55	341910N	0775634	1	USGS	F	U		GJ	75	73	2	T	39									Kpd	Obs [illegible]
56	341919N	0775526	1	JOHN G OWENS	P	H			40		1	X	25	7								Kpd-Tch	
57	341847N	0775531	1	MAGGIE L ALLEN	P	H			46		1	X		8								Kpd	
58	341844N	0775524	1	ST JAMES AME CH	P	T	P		54		2	X	36	10			5		1	6	3	Kpd	
59	341912N	0775510	1	US DEPT OF AGRI	F	I			45	35	3	X		5	100		6		0	5	3	Tch	
60	341920N	0775458	1	US DEPT OF AGRI	F	U		J	31		3	X	35	5								TQ	[illegible]
61	341839N	0775352	1	RAEFORD TRASK	P	U			27		1	T	35	5								TQ	
62	341918N	0775303	1	PAULINE CORE	P	H			72		2	X	28	6								Kpd	
63	341904N	0775208	1	RAEFORD TRASK	P	I		J	119		4	X	38	11								Kpd	
64	341912N	0775153	1	RAEFORD TRASK	P	I			64		4	X	40	4	*100							Kpd	
65	341845N	0775153	1	RAEFORD TRASK	P	I		J	98	84	6	X	38	8	250							Kpd	
66	341856N	0774628	1	E C BRINKLEY	P	H	P		14		36	X	48	11			1	6	2	3		TQ	

* Estimated. [1]pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp.Cond.	Water-bearing unit	Remarks
67	341902N	0774617	1	USGS	F	U		GJ	74	72	1	T	48									Tch	Obs. well, Auger #47
68	341905N	0774618	1	J C WELLS	P	H	C		70	60	1	X	50	26			5	6'	1	6	4	Tch	Temp. 66°F.
69	341913N	0774615	1	J F SWAN SR	P	H			100		2	X	50	28			8		1	6	3	Tch	
70	341911N	0774611	1	J F SWAN JR	P	H	C		172	130	2	X	46				6	6'	1	6		Kpd	
71	341816N	0774458	1	RALPH MOORE	P	H			30	22	2	X	24	11	15							Tch	Temp. 66°F.
72	341819N	0774450	1	HARRY L SMITH	P	H			20	18	1	T	20	9			0		2	5	3	TQ	Cl 2280 at [illegible]'
73	341754N	0774440	1	MR ORNESBY	P	H		JD	165	159	2	X	18	9			3	7				Kpd	
74	341753N	0774441	1	R G JOHNSTON	P	H	P		60		2	X					1	7	4	7		Tch	
75	341747N	0774444	1	E E CASTEEN	P	H	P		47	27	2	X		17			1	7	5	7		Tch	
76	341743N	0774611	1	COR-DAVIS HOME	N	T	P		181	131	6	X	25	10	*450			7'	3			Kpd	
77	341738N	0774634	1	JOHN F MURRAY	P	H	P				1	X	23	12			1	7	1	4		Tch	
78	341755N	0774628	1	C E RIVENBARK	P	I	P		75		6	X		17	450		1		0	4	2	Tch	
79	341820N	0774646	1	C E RIVENBARK	P	I		J	60	38	2	X	40	12								Tch	
80	341800N	0774714	1	R D DREW JR	P	H			55		2	X	42	21			5		0	5	3	Tch	
81	341741N	0774655	1	W J WILSON	P	H	P		21	19	1	T	24	15			7		0	2	2	TQ	
82	341731N	0774704	1	W J WILSON	P	I			81	32	6	X	29	18	275	23	6		1	5	3	Tch	
83	341738N	0774752	1	A L SOUTHERLAND	P	H			56	52	1	X	36	12			5		1	6	3	Tch	
84	341722N	0774803	1	G P WILSON	P	U			41		1	X	37	20								Tch	
85	341746N	0775048	1	JOHN D MURRAY	P	H	P		123		2	X	42	16			5		0	7	3	Kpd	
86	341745N	0775123	1	JOHN D OLSEN	P	H	C		120	105	2	X	34	13			4	7'	1	6	3	Kpd	
87	341741N	0775123	1	USGS	F	U	C		740	120	4	X	32									Kpd	Test [illegible] 11
88	341722N	0775223	1	ALEXENDER WEIDE	P	H			109	78	2	X	42	17						5		Kpd	
89	341817N	0775414	1	USGS	F	U		GJ	55	53	1	T	38									Tch	Ob[illegible] 11
90	341734N	0775406	1	RAEFORD TRASK	P	I		J	83		6	X	31									Kpd	

* Estimated. 'pH measured in field.

Table 5.--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
91	341711N	0775401	1	RAEFORD TRASK	P	I		J	90		8	X	28		300		4	7'	2	6	3	Kpd	Temp. 65°F.
92	341724N	0775436	1	CORNELIUS MOORE	P	C			21	19	1	T	34	12								TQ	
93	341720N	0775443	1	USGS	F	U		GJ	130	128	1	T	34	11								Kpd	
94	341722N	0775448	1	J C LONG	P	H		G	55	51	2	S	35	13	*20		1		1	2	1	TQ	
95	341751N	0775431	1	J L SMITH	P	H		J	62		2	X	34	13								Tcb-Kpd	
96	341758N	0775456	1	REED SMITH SR	P	H	P		55	42	2	X	30	9				7'				Kpd	
97	341818N	0775459	1	SWART SONS INC	N	U	P		367	309	8	X	35	1	*30			9	8			Kpd	Temp. 67°F., Sp. 22 [illegible]
98	341815N	0775512	1	A D COX	P	I			63		4	X	28	13	*50							Kpd	
99	341816N	0775516	1	A D COX	P	H			45		1	T	33	14								TQ	
100	341759N	0775507	1	G PLOTT	P	H			70	52	2	X	30	9								Kpd	
101	341754N	0775512	1	TINGA NURSERY	P	I			80	35	4	X	32		100'		6		1	5	3	Kpd	
102	341806N	0775530	1	E M STANLEY	P	H	P		67		2	X	*20	8	*100		7		1	6	4	Kpd	
103	341738N	0775532	1	C R WATTS	P	U			29	27	1	T	23	12								TQ	
104	341755N	0775612	1	ROY BROWN	P	H			26	24	1	T	26	20								TQ	[illegible]
105	341811N	0775630	1	E H TINGA	P	U			28	26	1	T	26	10								TQ	
106	341753N	0775836	1	USGS	F	U		GJ	57	47	2	S	14									TQ	
107	341700N	0775921	1	USGS	F	U		GJ	50	47	2	T	11									TQ	
108	341705N	0775902	1	CAROLINA POWER	N	N	C	D	53	33	10	G	8	9	480	7		5'				Kpd-TQ	Temp. 67°F.
109	341706N	0775849	1	CAROLINA POWER	N	N			55		10	G	12									Kpd-TQ	
110	341701N	0775831	1	USGS	F	U		GJ	57	54	2	T	18									TQ	
111	341706N	0775748	1	USGS	F	U	C	G	56	53	2	T	20				1	7	0	0	0	Kpd-TQ	
112	341651N	0775738	1	CAROLINA NITRO	N	N		D	84	56	8	G	44		280							Kpd-TQ	
113	341642N	0775734	1	CAROLINA NITRO	N	N	P	J	65	30	8	G	33	27	200	18						Kpd-TQ	
114	341634N	0775732	1	CAROLINA NITRO	N	N		D	60	40	8	G	24	23	200	13						Kpd-TQ	

* Estimated. [1]pH measured in field.

Table 5.--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
115	341631N	0775721	1	CAROLINA NITRO	N	N	C	D	72	47	8	G	24	23	80	20						Kpd	
116	341619N	0775741	1	JOHNNY MALPASS	P	H	P		25	23	1	T	12	5			5		0	1	1	TQ	
117	341619N	0775727	1	SWIFT AGRI CHEM	N	N			55	35	8	G		6	*100							Kpd	
118	341609N	0775719	1	ROBERTSON CHEM	N	H			21	18	2	T		4				5'	1			TQ	Reported high Fe
119	341605N	0775718	1	ROBERTSON CHEM	N	U			47		4	X	5	3			5		0	1	0	Kpd	
120	341558N	0775719	1	HORTON IRON MET	N	H			20	15	2	T	6									TQ	
121	341558N	0775713	1	HORTON IRON MET	N	N			40		4	X	5	2	*50		8		1	4	2	Kpd	
122	341613N	0775609	1	GROVER SCOTT	P	H			60	42	2	X		14								Kpd	
123	341623N	0775604	1	FRED TOWNSEND	P	H	C		60	42	2	X	24	17	*100		6	6'	1	4	3	Kpd	Temp. 66°F.
124	341706N	0775544	1	W F INGOLD	P	U			20	18	1	T	25	9								TQ	
125	341646N	0775524	1	EDGAR MCKOY	P	H		D	75	72	2	X			*50							Kpd	
126	341644N	0775517	1	M K MALPASS	P	H			78	70	2	X	28	12	*100							Kpd	
127	341624N	0775452	1	NEW HAN AIRPORT	M	U	P	DJ	89		8	X	29	15								Kpd	Specific cap. 34 gpm/ft.
128	341623N	0775455	1	NEW HAN AIRPORT	M	P			105	65	8	X		15	211	9						Kpd	
129	341616N	0775505	1	NEW HAN AIRPORT	M	P			102	93	8	X		17	300	8						Kpd	
130	341605N	0775523	1	PILOT FRGT INC	N	C			75	51	2	X	25	12								Kpd ?	
131	341550N	0775355	1	ADC DIS COMPLEX	F	P	C				8	X		8	425	13						Kpd	12" in 5x6 orifice
132	341545N	0775339	1	ADC DIS COMPLEX	F	P			96	74	8	X		1	445	8	5		2	5	3	Kpd	13" in 5x6 orifice
133	341623N	0775357	1	S H FEENSTRA	P	H	P		20	17	1	T	21	5			6		1	0	1	TQ	H_2S
134	341628N	0775357	1	S H FEENSTRA	P	I	C		113		8	X	20	0			5	7'	1	6	3	Kpd	Temp. 64°F.
135	341629N	0775351	1	S H FEENSTRA	P	I		J			4	X		2								Kpd	H_2S
136	341622N	0775332	1	FRED A JORDAN	P	U			25	23	1	T	21	6			5		1	2	1	TQ	H_2S
137	341649N	0775329	1	DOROTHY PEOPLES	P	H	P		22	20	1	T	24	4			7		1	2	1	TQ	H_2S
138	341652N	0775248	1	J N CORBETT	P	U			36	34	1	T	40	9								TQ	

* Estimated. 'pH measured in field.

Table 5.--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
139	341649N	0775249	1	E E LEWIS	P	H	C		121	90	2	X	41	5	*130		3	7	0	5	3	Kpd	Temp. 66°F.
140	341641N	0775240	1	G W SHEARON	P	H	P		115	110	2	X					5		0	5	3	Kpd	
141	341626N	0775241	1	HARRELLS BLDG	N	I		J	87		6	X	29	3			6	7'	0	5		Tch-Kpd ?	Temp. 65°F.
142	341635N	0775147	1	HERBERT NEWTON	P	H					2	X	38	19			5	8	0	5	4	Kpd ?	
143	341629N	0775139	1	RAYMOND MCKOY	P	H	P		20	17	1	T	45	5								TQ	
144	341610N	0775045	1	E F PRIDGEN	P	P		D	146	92	2	X	41	21			5		0	5	3	Kpd	
145	341608N	0774923	1	NEGRO CHURCH	P	T		J	87		4	X	46	6								Tch	
146	341616N	0774907	1	J W COVIL	P	C	P		75		2	X		18	*60		6		1	6	3	Tch	High Fe
147	341613N	0774857	1	CHRISTIAN CH	P	T	C		65	50	2	X	45	12				7'				Tch	Temp. 68°F.
148	341646N	0774858	1	FRANK PARKER	P	H		J	155	60	2	X	47									Tch-Kpd	
149	341646N	0774842	1	BAYSHORE EST	N	U		J	68		2	X	44	9								Tch	
150	341639N	0774830	1	E K CARTER JR	P	H	P				1		31				4		0	4	2		
151	341634N	0774758	1	M L HONEYCUTT	P	H		G	80	40	2	X	16	12								Tch	
152	341641N	0774750	1	M P RAINES	P	H		G	90		2	X	20	13	*30		5		1	5	3	Tch	
153	341637N	0774747	1	D P HERBERT	P	H			50	41	2	X		15	*20							Tch	
154	341654N	0774739	1	M MARSHBURN	P	H	C		150	110	2	X	23					7'				Kpd	Tem. 66°F., much H_2S
155	341648N	0774642	1	W J ROBINSON	P	H	C		60	55	1	X	10				2	7'	2	5	3	Tch	Temp. 66°F.
156	341723N	0774503	1	C M DAVIS	P	H	P		85			X					0		3	4	3	Tch	
157	341712N	0774510	1	M H BELL	P	H	P		120		2	X					0	8	2	5		Tch	
158	341659N	0774522	1	G A RYALS	P	H			180	126	2	X	20	15	*50		5		2	6	4	Kpd	
159	341654N	0774525	1	J N MCCARTNEY	P	H	P		42	40	1	X					0	8	5	7		Tch	
160	341652N	0774526	1	G D FARMER	P	H	C		180	127	2	X	20	15				7'				Kpd	Temp. 66°F.
161	341631N	0774548	1	CAMERON - TRASK	P	H	P		38		1	T					1		1	5	3	TQ	
162	341629N	0774552	1	CAROLINA POWER	N	H	P		70		2	X					0		1	4	2	Tch ?	

* Estimated. 'pH measured in field.

Table 5.--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water Iron	pH	Cl	Hardness	Sp.Cond.	Water-bearing unit	Remarks
163	341613N	0774628	1	J N CORBETT	P	U		J	65		2	X	5									Tch	Reported brackish
164	341613N	0774624	1	P R MASON	P	H	P		42		1	X	8	9	*20		2		4	7	5	Tch	H_2S odor
165	341539N	0774700	1	ROBERT JAMES	P	H			60		2	X	23	17	15		5	7	0	4	2	Tch	Temp. 67°F.
166	341530N	0774653	1	GEORGE HULBERT	P	H			48	42	2	X	27	27								Tch	
167	341525N	0774643	1	DR HK THOMPSON	P	H	C		165		3	X		30								Kpd	
168	341515N	0774653	1	L M MERRILL	P	A	P		186	124	4	X	6	8	250		2	7	2	6		Kpd	1.1 ppm H_2S
169	341512N	0774735	1	DR WC VONGLAHN	P	H		D	83	64	4	X	24	16	*40		5		1	6	3	Tch	
170	341557N	0774837	1	OGDEN SCHOOL	C	P		D	93	68	6	X	31	12	250		4		1	6	3	Tch	
171	341527N	0774910	1	W E COVIL	P	I			204		6	X	19	2	400		2		1	6	4	Tch-Kpd	H_2S odor
172	341535N	0774941	1	E B TOWLES	P	P			163	81	4	X	*39	19								Tch-Kpd	
173	341537N	0774944	1	E B TOWLES	P	P		J	157	64[1]	2	X	44									Tch-Kpd	
174	341549N	0774949	1	J D HENEGAR SR	P	H			162	95	2	X	46				4		1	6	4	Kpd ?	
175	341531N	0774958	1	NC HWY PATROL	S	H	C	D	180	86	6	X		30	165		5	7	1	6	4	Tch-Kpd	
176	341515N	0775040	1	CHARLES WELLS	P	H		G	153	63	2	X	44	17	*70		5		0	5	3	Tch-Kpd	Temp. 67°F.
177	341426N	0775115	1	RICHARD NAPIER	P	H	C		160	130	4	X	47					7				Kpd	Temp. 68°F.
178	341454N	0775128	1	COLL VIEW TRLR	P	P	C		62		2	X		8	60[1]		4	7	1	5	3	Tch	Temp. 65°F.
179	341457N	0775144	1	JOHN TAYLOR	P	H	P		130	60	2	X	38	7			5		1	2	1	Tch-Kpd	
180	341457N	0775144	2	JOHN TAYLOR	P	U	P		30	24	1	T	38	6			5		1	2	1	TQ	
181	341508N	0775213	1	CORNING GLASS	N	U		DJ	140		8	G	27	7	250	60	5	8	2	6	3	Kpd	Temp. 66°F., H_2S odor
182	341522N	0775218	1	HOME REALITY	N	C	P		25	21	2	T	31	8			3		0	2	1	TQ	
183	341446N	0775220	1	B W PARSONS	P	P			25	21	2	T		9								TQ	
184	341444N	0775241	1	W K RHODES	P	H		D	96	53		X		8	10	10						Tch-Kpd	
185	341526N	0775304	1	J D DILL	P	H	P		80		2	X					0	8	2	4	3	Kpd	Temp. 65°F.
186	341551N	0775311	1	M L BLAKE	P	H	P	D	87	79	4	X	17	6	*100		3		1	5	3	Kpd ?	

* Estimated. [1]pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
187	341525N	0775315	1	ALLENDALE DEV	P	U			29		1	T	21	11								TQ	
188	341526N	0775325	1	E C AKERS	P	H			70	43	2	X	15									Kpd	Flows
189	341519N	0775328	1	H C JOHNSTON	P	H			92		2	X	28	15								Kpd	
190	341438N	0775321	1	LEON SULLIVAN	P	P			129	42	3	X	38	16	100[1]							Tch-Kpd	
191	341432N	0775313	1	SANDRE - BASS	P	H			151	57	2	X	40	22								Tch-Kpd	
192	341431N	0775320	1	BECKERS BLDS	N	C	C		150	105	2	X	42		*40		5	7[1]	1	6	3	Kpd	Temp. 67°F.
193	341405N	0775426	1	D L SNEEDEN	P	S			130	35	2	X	36	10								Tch-Kpd	
194	341402N	0775434	1	JOS FREEDLAND	P	A		D	89	72	4	X		12	*100							Tch-Kpd	
195	341405N	0775435	1	B W NEWKIRK	P	H		D	87	40		X		19	*60							Tch-Kpd	
196	341430N	0775448	1	BNAI ISR SYNAG	P	A		D	94	15		X	35	8	100	14						Tch-Kpd	
197	341411N	0775512	1	RUDOLPH KONIG	P	H		D	75	27	4	X					1		1	6	3	Tch-Kpd	
198	341441N	0775511	1	J FRED MURRAY	P	I		D	97	75	4	X	28	25	*100		5		1	5	3	Kpd	
199	341438N	0775515	1	R L DAVIS	P	I		G	90	34	2	X	28	24								Tch-Kpd	
200	341517N	0775544	1	SOUTHERN BOX	N	N	P		85		6	X	21	20	185				2	5		Kpd	
201	341507N	0775621	1	BOYLE ICE CO	N	C			65		8	X			650				2			Kpd	
202	341530N	0775651	1	HILTON PARK CO	M	U	P	G	1330		6	X	9		*50		5	8	8	5	8	Kpd ?	Temp. 70°F., Br 31 ppm
203	341512N	0775653	1	HILTON PARK CO	N	U			80		10	X	10	6	400							Kpd	
204	341437N	0775636	1	INDEPENDL T ICE	N	U			120	75	12	X			325	6			2	6		Kpd	
205	341417N	0775616	1	COCA COLA BOTT	N	C	P		180		4	X	44	19	*80		2		1	5	3	Kpd	
206	341413N	0775618	1	WARDS FUNERAL	N	U		J	82		4	X	53									Tch-Kpd	
207	341407N	0775644	1	PEOPLES SAVINGS	N	A			86		6	X	38	31	100	12						Kpd	Fe bacteria rptd.
208	341407N	0775644	2	PEOPLES SAVINGS	N	A		D	122	108	8	G	38	44	96		2	8	2	4	3	Kpd	
209	341407N	0775644	3	PEOPLES SAVINGS	N	A	C	D	133	110	8	G	36	41	97	13						Kpd	
210	341430N	0775655	1	WILM COLD STOR	N	C		J	104		10	X	21	26								Kpd	

* Estimated. [1]pH measured in field.

Table 5.--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
211	341412N	0775702	1	WACHOVIA BANK	N	U			80		6	X							3			Kpd	Test well
212	341409N	0775738	1	USGS	F	U	P	G	93	91	1	T	4				5	7	3	6		Kpd	Auger hole Ø40
213	341403N	0775818	1	TERMINAL CITY	N	C			63		3	S	4	8	*6							Kpd	
214	341407N	0775609	1	ROSE ICE CO	N	C			96		6	X										Tch-Kpd	Cl rept. 62 ppm in 1942
215	341407N	0775605	1	NEW HAN HIGH SC	C	P		D	122	50	6	X		18	165							Kpd	
216	341349N	0775637	1	5TH AVE BAPT CH	P	T		D	90	58	6	X	45	18	*35							Kpd	
217	341331N	0775646	1	BRIGADE BOYS CL	P	T		J	115	40	4	X	47	42								Kpd	
218	341330N	0775522	1	PEPSI COLA BOTT	N	C		D	75	41	8	X	37	11	220	20	5		0	5	3	Tch-Kpd	
219	341324N	0775521	1	WHITEBROOK FARM	N	C					8	X	38		150							Tch-Kpd	Rept. Cl 62 ppm, Hard. 210
220	341314N	0775442	1	ALBERT PERRY	P	I	P		163	58	3	X	35		*80		5		0	5	3	Tch-Kpd	
221	341327N	0775434	1	L B FINBERG	P	I			135		4	X			*100							Tch-Kpd	
222	341306N	0775356	1	R A YOPP	P	H		G	135	100	4	X	40	2								Kpd	
223	341329N	0775341	1	J D PRIDGEN	P	H			25	21	1	T	28	7	*10							TQ	
224	341302N	0775352	1	D E JOHNSON	P	H	P	G	140	50	2	X	38	9	*40		4		1	6	3	Tch-Kpd	
225	341243N	0775331	1	W S ARTHURS	P	H			98	58	2	X	42	10								Tch	
226	341337N	0775312	1	L J MINTZ	P	H		D	140	86	4	X	38	28	165		5		1	6	3	Kpd	
227	341416N	0775206	1	W D MCKEE	P	H		J	135	60	2	X	41									Tch-Kpd	
228	341337N	0775239	1	WILM COLLEGE	S	A	P	D	165	80	10	G		12	340	80	2	8	2	6	3	Tch-Kpd	Temp. 66°F.
229	341330N	0775236	1	WILM COLLEGE	S	U		J	84		4	X	42									Tch	
230	341336N	0775232	1	WILM COLLEGE	S	A	P	D	180	80	10	G		7	360	50						Tch-Kpd	
231	341303N	0775236	1	M J PIERCE	P	H	P	D	170	80	2	X	42		*60		4		0	5	3	Tch-Kpd	
232	341255N	0775231	1	MRS EARL BIGGS	P	H			35	31	1	T	40	13			4		1	1	1	TQ	
233	341237N	0775252	1	ANDY MASON	P	H		G	159	76	2	X	*42									Tch-Kpd	
234	341233N	0775231	1	E R WILSON	P	H		D	163	82	4	X	41	30			3		1	5	3	Kpd	

* Estimated.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp.Cond.	Water-bearing unit	Remarks
235	341236N	0775216	1	RUSSELL KEY	P	H		D	147	71	4	X	*35	15			3		0	5	3	Kpd	
236	341253N	0775211	1	EVA BERKLEY	P	H			160	78	2	X	39	16								Tch-Kpd	
237	341250N	0775203	1	LESTER ROBINSON	P	H			87	79	4	X		8	*35							Tch	
238	341251N	0775158	1	D W BENNETT	P	H		G	165	86	2	X	*32	16	*60		3		0	4	2	Kpd	
239	341244N	0775150	1	CAPE FEAR HOSP	P	T		J	154		6	X	34				2		2	5	3	Tch-Kpd	
240	341253N	0775148	1	B L FOWLER	P	H			146	70	2	X	34	14								Tch-Kpd	
241	341259N	0775139	1	L A BARNES	P	H			150	60	2	X	30	6	*40		1		0	5	3	Tch-Kpd	
242	341258N	0775134	1	R E HARRELL	P	H		G	159	64	2	X	30		75		3		1	5	3	Tch-Kpd	Obs well
243	341257N	0775127	1	E C ORRELL	P	H		J	139	60	2	X	25									Tch-Kpd	
244	341321N	0775050	1	J P ELLINGTON	P	H	P	P	145	60	2	X	8	6			0	7'	2	5	4	Tch-Kpd	Temp 65°F, Flow 12 [illegible]
245	341248N	0775029	1	A B POWLASS	P	H			160	59	2	X	15	15								Tch-Kpd	
246	341314N	0774956	1	J J DENNING	P	H			170	120	2	X	24	16			2	8'	2	5	4	Kpd	
247	341240N	0774958	1	BRAD CK MARINA	N	C			178	65	8	X	21	17	500							Tch-Kpd	Rept yield
248	341246N	0774917	1	WSR BEANE	P	H			175	74	4	X		17								Tch-Kpd	
249	341318N	0774906	1	EARL MILLER	P	H	C		100	64	2	X	15	9				7'				Tch	
250	341316N	0774902	1	BABIES HOSPITAL	P	T		D	136	72	6	X		8	250							Tch	
251	341313N	0774859	1	BABIES HOSPITAL	P	T		D	107	62	6	X		8	650							Tch	
252	341308N	0774856	1	WATERWAY MOTEL	P	C		J	172		6	X	10									Tch-Kpd	
253	341248N	0774813	1	WRIGHTSVILLE BE	M	P	C		182	140	8		3	40	200							Kpd	
254	341253N	0774753	1	JOHN ANDERSON	P	U		GJ	169	128	2	X	5	15	60	15	3		2	5	4	Kpd	
255	341303N	0774717	1	WRIGHTSVILLE BE	M	P	C		179	163	10		8	40	150							Kpd	
256	341253N	0774730	1	WRIGHTSVILLE BE	M	P	C		176	146	10		10		150							Kpd	Has yielded 300 gpm
257	341239N	0774736	1	WRIGHTSVILLE BE	M	P	C		193	156	8		10		140							Kpd	Tested at 420 gpm for 10 hrs.
258	341227N	0774749	1	WRIGHTSVILLE BE	M	P	C		180				6	35	175							Kpd	

* Estimated. [1]pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
259	341207N	0774804	1	WRIGHTSVILLE BE	M	P	C		180		8		6		175							Kpd	
260	341148N	0774813	1	WRIGHTSVILLE BE	M	P	C		178				10	30	175	23						Kpd	
261	341140N	0774820	1	WRIGHTSVILLE BE	M	U	P	GE	412			X	5									Kpd	Stratigraphic test
262	341118N	0774837	1	WRIGHTSVILLE BE	M	P	C		174	160	10		8	32	150	90						Kpd	
263	341135N	0775024	1	L M WALLACE	P	H		J	165		2	X	19	24								Tch-Kpd	
264	341216N	0775046	1	U R CARROLL	P	H	C	G	70	54	2	X	25	13			5	7'	1	5	3	Tch	
265	341216N	0775046	2	U R CARROLL	P	U	P		29	25	1	T	25	14			6		1	2	1	TQ	
266	341209N	0775114	1	M E ROGERS	P	H			150	80	2	X	18	12			4		1	5	3	Tch-Kpd	Temp. 66°F.
267	341209N	0775114	2	M E ROGERS	P	U			34	30	1	T	18	13								TQ	
268	341139N	0775114	1	DR W A PHILLIPS	P	S			110	45	2	X										Tch	
269	341222N	0775134	1	A H HARRELL	P	H			100	70	2	X		16								Tch	
270	341217N	0775136	1	J O PETTET	P	H			100	72	2	X	18	8								Tch	
271	341215N	0775144	1	W H RIVENBARK	P	H			100	70	2	X	23	10								Tch	
272	341201N	0775146	1	W S SLATER	P	H			140	70	2	X	14	2								Tch-Kpd	
273	341215N	0775149	1	A M FOSTER	P	H			100	73	2	X	21									Tch	
274	341221N	0775157	1	V K PAINTER	P	H		J	134		2	X	26									Tch-Kpd	
275	341202N	0775151	1	ROBERT MEADOWS	P	H			85	63	2	X	15	3				7'				Tch	
276	341135N	0775202	1	RAY HOLLAND	P	H	P		177	80	2	X	12	12			1	7'	2	5	4	Tch-Kpd	Flows 1-6 gpm
277	341200N	0775227	1	W GRANEY	P	H		J	149	130	2	X	27	8								Kpd	
278	341202N	0775309	1	JACK ROGERS	P	H	P	G	162	81	2	X	44				3		0	5	3	Tch-Kpd	
279	341223N	0775403	1	GILBERT PARRISH	P	H			150	110	2	X	45	21								Kpd	
280	341227N	0775408	1	W F ELMORE	P	H		G	150		2	X	48	11								Tch-Kpd	
281	341231N	0775412	1	R P BROWN	P	H	C		140	100?	2	X	41					7'				Tch-Kpd	Temp. 65°F.
282	341245N	0775412	1	W F ANDERSON	P	H			140		2	X	41	21								Tch-Kpd	

'pH measured in field.

Table 5.--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	Fe	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
283	341238N	0775452	1	DR S V ALLEN	P	I	P		19	16	1	T			*15		7		2	2	2	TQ	
284	341234N	0775502	1	W B BEERY III	P	I			155		6	X	33									Kpd	
285	341230N	0775450	1	MR STALLWORTH	P	H			158	66	3	X	45	29	*100							Kpd	
286	341206N	0775457	1	C R BRINDELL	P	H			160	60	2	X	55	46	*20							Tch-Kpd	
287	341238N	0775547	1	GEORGE LAMICA	P	H	C		30	24	2	X	22				2	7'	0	4	2	Tch	
288	341220N	0775553	1	JOHN W DIXON JR	P	H	C		110	90	2	X	*7	1			1	8'	0	4	2	Kpd	[illegible]
289	341220N	0775613	1	LEE E MORROW	P	H			26	22	1	T	10	3								TQ	
290	341207N	0775630	1	SUNSET PK METH	P	T		D	82		8	X	19	15								Kpd	
291	341202N	0775638	1	SUNSET CO 3	N	U	P		140		6	G			132				2	3		Kpd	[illegible]
292	341214N	0775639	1	SUNSET CO 4	N	U			140		6	G			150	18						Kpd	
293	341210N	0775654	1	BILL CANNON	P	U			20	16	1	T	23	11								TQ	
294	341146N	0775703	1	WILM SHIPYARD	F	C		D	123	70	10	G		20	275	58						Kpd	
295	341141N	0775703	1	WILM SHIPYARD	F	U	P							13								Kpd	
296	341132N	0775702	1	WILM SHIPYARD	F	A	P		103	81	10	G		28	300	48	1	8	1	3	2	Kpd	
297	341126N	0775708	1	SHELL OIL CO	N	C	P		76	36	8	X		6	*325	6	7	7	2	4		Kpd	
298	341125N	0775630	1	WECT TV	N	A			133	55	4	X	52	26	100'							Tch-Kpd	
299	341127N	0775609	1	MOFFIT VILLAGE	N	P		G	175		10		43	9	140	37						Tch-Kpd ?	
300	341138N	0775606	1	L W CARROLL	P	H			57	44	4	X	*30	14			7		0	4	2	Tch	
301	341120N	0775555	1	NATL YOUTH ASSN	P	U		D			6		56	24								Tch-Kpd	
302	341112N	0775559	1	HANOVER MILLS	N	N			157	79	8	X	57	30	*100	17		8	1			Tch-Kpd	
303	341058N	0775555	1	H B LUDLUM	P	H		G	140	76	2	X	56	17								Tch-Kpd	
304	341134N	0775406	1	J R KUTRON	P	H	P		160	60	2	X	40		*40		5		0	5	3	Tch-Kpd	
305	341139N	0775357	1	H M DANIELS	P	H	P		160		4	X	48		100'		6		0	6	3	Tch-Kpd	
306	341124N	0775357	1	FRED CONNER	P	H	P		160	60	3	X	50	19			5		0	6	3	Tch-Kpd	

* Estimated. 'pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
307	341107N	0775406	1	G L KEIFER	P	H		J	146		2	X	39	14								Tch-Kpd	
308	341115N	0775340	1	S FOREST JR	P	H	C		150	79	2	X	50	21			3	7'	0	5	3	Tch-Kpd	H_2S odor
309	341114N	0775334	1	W H BANNERMAN	P	H	C		80	70	2	X	50	18	*17		3	7'	0	5	3	Tch	
310	341113N	0775331	1	MARGARET JONES	P	H	P		170	94	2	X	50	27	*60							Tch-Kpd	
311	341116N	0775316	1	J D MCFAYDEN	P	H			170	84	2	X	*51	18								Tch-Kpd	
312	341110N	0775318	1	D W NOBLES	P	H		J	154		2	X	50		*40							Tch-Kpd	
313	341103N	0775318	1	J M GAITHER	P	H		G	170	89	2	X	50	29								Tch-Kpd	
314	341045N	0775142	1	PARSLEY ESTATE	P	U			158		4	X	28	23								Tch-Kpd	
315	341103N	0775137	1	HERMAN WALTON	P	C	P		62		2	X	15	4	*80		5		1	5	4	Tch	
316	341101N	0775042	1	C R MALOTT	P	H	C		163	125	3	X	*12	9	*100		2	8'	2	5	4	Kpd	Partial fro[illegible] o[illegible] w[illegible]
317	341052N	0775036	1	H V REID	P	H	C	D	94	90	4	X	12	10	100		5	8	2	6	4	Tch	
318	341042N	0775043	1	A D HURST	P	H	P		44		1	T	12	11			3		1	6	3	TQ	
319	341040N	0775044	1	A D HURST	P	U			66		2	X	15	13								TQ	
320	341030N	0775054	1	JAMES FERGER	P	I	P		185		2	X	*21		*60		2		2	5	3	Tch-Kpd	H_2S odor
321	341000N	0775105	1	C H MCALLISTER	P	I	P		144	85	3	X		10			2		1	6	3	Tch-Kpd	
322	340938N	0775119	1	R E JULIAN	P	H	P		150	85	2	X		30			3		1	5	3	Tch-Kpd	
323	340935N	0775134	1	D F SUTHERLAND	P	H	P	D	124	86	6	X		18			2		1	5	3	Tch-Kpd	
324	340950N	0775146	1	R C FOWLER	P	H			80	72	2	X		22								Tch	
325	340939N	0775155	1	A B JENKINS	P	H			100	70	2	X		15								Tch	
326	340926N	0775152	1	H H HODGIN	P	H	P		140	105	2	X	*18	19			5		0	5	3	Tch	
327	340914N	0775212	1	M EMMART JR	P	H	P		140		2	X		20			0		1	5	3	Tch	
328	340954N	0775235	1	W J HODDER	P	U			175		2			6								Tch-Kpd	
329	340958N	0775239	1	W J HODDER	P	I		J	170		4	X	21	14								Tch-Kpd	Obs. well
330	341018N	0775320	1	M R SOMERSETT	P	H			160	84	2	X	44	17								Tch-Kpd	

* Estimated. [1]pH m[illegible]ured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
331	341012N	0775320	1	A L TODD	P	H	C		100		2	X						7'				Tch	Temp. 66°F.
332	341025N	0775520	1	W J LANGLEY	P	P	P		117		2	X	30		60*		4		0	5	2	Tch-Kpd	
333	341037N	0775528	1	ONIETA DAVIS	P	H	P		120		2	X					4		0	4	2	Tch-Kpd	
334	341034N	0775539	1	E J BELLAMY	P	H		J	108		2	X	30	12								Tch-Kpd	
335	341036N	0775607	1	TENNY ENGINEERS	N	N	P	D	120	104	6	X		9	226		2	8'	2	4	2	Kpd	Temp. 67°F.
336	341037N	0775611	1	TENNY ENGINEERS	N	N		D	122		6	X		11								Kpd	
337	341030N	0775619	1	USGS	F	U		G	38	36	1	T	36									TQ	Obs. well, auger hole #19
338	341015N	0775654	1	STACKHOUSE INC	N	N	P		135		4	X					1		2	4	3	Kpd	H_2S odor
339	341006N	0775519	1	ECHO DAIRY	P	C	P		160	70	6	X			150		4		1	5	3	Kpd	
340	340949N	0775522	1	ECHO DAIRY	P	H	P		160	70	4	X		10	100*		2	7'	2	4	3	Kpd	Temp. 67°F.
341	340939N	0775533	1	ECHO DAIRY	P	I	P		48		10	X	3	15			0	8	2	4	3	Kpd	Flows
342	340909N	0772620	1	ALLIED KENNECOT	N	U	P	GJE	142		10	G	17	13	600				2			Kpd-TQ	
343	340909N	0775628	1	ALLIED KENNECOT	N	N	C	J	151		8	S	12	6	60	15		8'	3			Kpd	Obs. well, Temp. 67°F.
344	340907N	0775440	1	G H COOK	P	H	P		132	72	2	X	10	1			0		2	4	3	Kpd	
345	340905N	0775406	1	J A EDWARDS	P	H	P		30		1	T	22				6	6'	1	4		TQ	Temp. 65°F.
346	340905N	0775406	2	J A EDWARDS	P	I	P		62		1	T	22				7	7'	1	6		TQ	
347	340905N	0775406	3	USGS	F	U	C	GJE	630		6	X	22									Kpd	Test well
348	340905N	0775413	1	W I MILLER	P	U			35		1	T	23	8								TQ	
349	340902N	0775410	1	J A EDWARDS	P	H	C		165	130	4	X	23	14			1	8'	2	4	3	Kpd	
350	340842N	0775426	1	HUGH NOFTSINGER	P	H	P		37	33	2	T	*20	8	8		5		0	1	0	TQ	Much H_2S
351	340829N	0775344	1	MR PRESLEY	P	P		D	161	74	4	X	20	7	250							Tch-Kpd	
352	340802N	0775351	1	N W DINKINS	P	H		G	130	112	2	X	36	21	*15		4		0	4	2	Kpd	
353	340802N	0775351	2	N W DINKINS	P	U			18		1	T	36	11								TQ	
354	340811N	0775334	1	W E HARRIS	P	H	P		140	92	2	X	37	16	*50		4		0	4	2	Tch-Kpd	

* Estimated. [1]pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
355	340803N	0775337	1	GEO W JAMES	P	H			155	107	2	X	42	20								Tch-Kpd	
356	340807N	0775246	1	OTTIE SULLIVAN	P	H	P		200+		4	X	28	16			2		1	6	3	Tch-Kpd	
357	340815N	0775243	1	FERGER NURSERY	P	C	P		57		2	T	28	11			6		1	6	4	TQ	
358	340825N	0775236	1	M S EMMART	P	H			50		1	T	29	17								TQ	
359	340803N	0775234	1	W G SUTHERLAND	P	U			18	16	1	T	26	6								TQ	High Fe rept.
360	340800N	0775234	1	USGS	F	U		GJ	161	159	2	T	26	15								Kpd	Obs. well, auger hole #29
361	340756N	0775203	1	M K LOUGHLIN	P	C	P	D	185	119	4	X	5	6	50	7			3	6	5	Tch-Kpd	
362	340755N	0775209	1	JOHN HINEBUCKLE	P	H	C		135	115	2	X	10	4	5	19		7'				Tch	
363	340739N	0775210	1	T E RUSS	P	U			150	75	1	X	5	13								Tch	
364	340745N	0775238	1	C K JOHNSON	P	U			85		2	X	23	14								TQ	
365	340733N	0775212	1	JULIAN GRISSOM	P	H	P	D	125	120	4	X	5		50'		3		0	5	3	Tch	Flows
366	340727N	0775246	1	W T BRYAN	P	H	P		148	116	2	X		18								Tch	
367	340710N	0775243	1	ROBERT B LONG	P	H	P		137		1	X		15			2		0	3	2	Tch	
368	340732N	0775423	1	USGS	F	U	P		65	63	1	T	38	15			2	8'	0	3	2	TQ	
369	340720N	0775352	1	MR ROLLER	P	H			121	85	2	X	40	26								Tch	H_2S odor
370	340716N	0775354	1	A E ROLLER	P	H			140	123	2	X	34									Kpd	
371	340714N	0775356	1	R H DINGLER JR	P	H	C		119	104	2	X	40	15				8'				Tch	
372	340638N	0775258	1	HAMP BOWEN	P	H	C	G	147	128	2	X	28	18				7'				Tch-Kpd ?	Temp. 66°F.
373	340630N	0775308	1	PAUL GRIFFIN	P	H	P	D	135	122	4	X	28	18	100		5		0	5	2	Tch	
374	340622N	0775312	1	C L BOWDEN	P	H	P		112	100	2	X	22	9			1	8'	0	5	2	Tch	
375	340622N	0775312	2	C L BOWDEN	P	U	P		17		1	T	22	7			7	6	2	1	1	TQ	
376	340624N	0775357	1	J L ENGLISH	P	C	P		23	20	1	T	40	4	10		5		0	1	0	TQ	H_2S odor
377	340614N	0775403	1	K L KYE	P	U		J	133		2	X	35	14								Tch-Kpd	
378	340611N	0775403	1	W H BLACKLEDGE	P	C	P		25		1	T	31				1		0	0	0	TQ	

'pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
379	340530N	0775346	1	LEE DAVIS	P	H	P		133	105	4	X	26	15	*200		0		1	4	2	Tch	
380	340528N	0775346	1	LEE DAVIS	P	U			17		1	T	24	6			2		2	3	3	TQ	
381	340530N	0775325	1	H H HARWARD	P	I	C	D	75	52	1	X	26	14	100							TQ	
382	340527N	0775327	1	C K STALLINGS	P	H		D	70	58	4	X	22									TQ	
383	340447N	0775347	1	ALFRED MITCHELL	P	H	C		132	91	2	X	22	12	*20		0	9'	1	4	2	Tch	
384	340420N	0775325	1	A M GOODSON	P	H			140	113	2	X	11	15								Tch	
385	340421N	0775340	1	W L BURNETT SR	P	H	P		90		2	X	15		30'		6		0	3	2	Tch	
386	340416N	0775342	1	G T FOWLER	P	U			29	26	1	T	15	6								TQ	High Fe rept.
387	340342N	0775332	1	RICHARD DAILY	P	C			55		1		6	2								TQ	
388	340340N	0775330	1	RICHARD DAILY	P	C	C	G	150	119	2	X	6	2	*20		0	7'	1	5	3	Tch	
389	340340N	0775359	1	A FREEMAN	P	U		J	104		2	X	22	14								Tch	
390	340336N	0775454	1	USGS	P	U	C	G	49	47	1	T	16	6			2	7'	0	2	1	TQ	Obs. well, auger hole [illegible]
391	340313N	0775404	1	MCMEEKIN CONST	N	U			105	104	2	X	19	8	*30							TQ	
392	340317N	0775347	1	OCEAN REALTY	N	H		J	83		2	X	9	4								TQ	
393	340218N	0775355	1	V MARTIN	P	U		J	143		2	X	16	21								Tch	
394	340213N	0775419	1	R E WEEKS	P	H		J	167	159	2	X	26	38								Tch	
395	340210N	0775350	1	CAROLINA BEACH	M	P	C		201	96	8	X										Tch	
396	340159N	0775351	1	CAROLINA BEACH	M	P	C		195	125	8	X										Tch	
397	340158N	0775437	1	CAROLINA BEACH	M	P	C		161		8	X		27	150	33						Tch	
398	340151N	0775411	1	CAROLINA BEACH	M	P	C		189		10	X		23	150	50						Tch	
399	340147N	0775357	1	CAROLINA BEACH	M	P	C		195	125	8	X			300							Tch	
400	340143N	0775343	1	CAROLINA BEACH	M	P	C		180	125	8	X										Tch	
401	340138N	0775344	1	GRAHAM HARWARD	P	H		J	140		4	X	8	16								Tch	
402	340109N	0775412	1	WILMINGTON BCH	N	P	P		147	90	10	X			80'		2		2	7	4	Tch	

* Estimated. 'pH measured in field.

Table 5 .--Records of wells in New Hanover County, N. C.--Continued

Well No.	Well location Lat	Well location Long	Sequence No.	Owner	Ownership	Use of water	QW analysis	Log data	Depth (feet)	Depth cased (feet)	Diameter (in)	Finish	Altitude of LSD (feet)	Water level (feet below LSD)	Yield (gpm)	Drawdown (feet)	Quality of water: Iron	pH	Cl	Hardness	Sp. Cond.	Water-bearing unit	Remarks
403	340145N	0775414	1	WILMINGTON BCH	N	P	P		153	90	10	X			100[1]							Tch	
404	340123N	0775418	1	INTERNATL NICKE	N	U		J	126		1	X	18	23								Tch	Salty water rept.
405	340110N	0775421	1	KURE BEACH	M	P	C		202	115	8	X	17	26	265		3		2	7	4	Tch	
406	340122N	0775501	1	ETHYL DOW	N	U	C	J	158		6	X	18		150			8				Tch	Obs. well
407	335941N	0775435	1	KURE BEACH	M	P	C	GJ	180	120	8	X	17	21	170	30			2	6	3	Tch	Temp. 67°F.
408	335933N	0775433	1	JAMES TEETER	P	U			15		1	T	14	11								TQ	
409	335913N	0775506	1	701ST RADAR SQ	F	A	C	D	150	109	4	X			*35							Tch	
410	335850N	0775503	1	701ST RADAR SQ	F	A	C	D	201	112	10	X	21	21	250		3		3	6	4	Tch	
411	335849N	0775506	1	701ST RADAR SQ	F	P	C		172	150	10	X			250							Tch	
412	335735N	0775628	1	FT FISHER FERRY	S	P	C	D	170		6	X	10	12	30	10						Tch	

* Estimated. [1]pH measured in field.

Explanation of Quality of Water Code

Constituent	Range (mg/l)	Code Number
Iron	0.00-0.05	0
Do	0.06-0.1	1
Do	0.11-0.30	2
Do	0.31-0.50	3
Do	0.51-1.0	4
Do	1.1 -3.0	5
Do	3.1 -5.0	6
Do	5.1 -10	7
Do	11 -15	8
Do	More than 15	9
pH	4.0 -4.9	4
Do	5.0 -5.9	5
Do	6.0 -6.9	6
Do	7.0 -7.0	7
Do	8.0 -8.9	8
Chloride	0 -10	0
Do	11 -25	1

Constituent	Range (mg/l)	Code Number
Chloride	26-100	2
Do	101-250	3
Do	251-500	4
Do	501-1000	5
Do	1001-2000	6
Do	2001-5000	7
Do	5001-20,000	8
Hardness	0-10	0
Do	11-20	1
Do	21-50	2
Do	51-100	3
Do	101-150	4
Do	151-200	5
Do	201-300	6
Do	301-500	7

Characteristic	Range (micromhos)	Code Number
Sp. Cond.	0-50	0
Do	51-150	1
Do	151-300	2
Do	301-500	3
Do	501-1000	4
Do	1001-2000	5
Do	2001-5000	6
Do	5001-10,000	7
Do	10,001-20,000	8

SIMULATION OF GROUND-WATER FLOW IN THE COASTAL PLAIN AQUIFER SYSTEM OF NORTH CAROLINA

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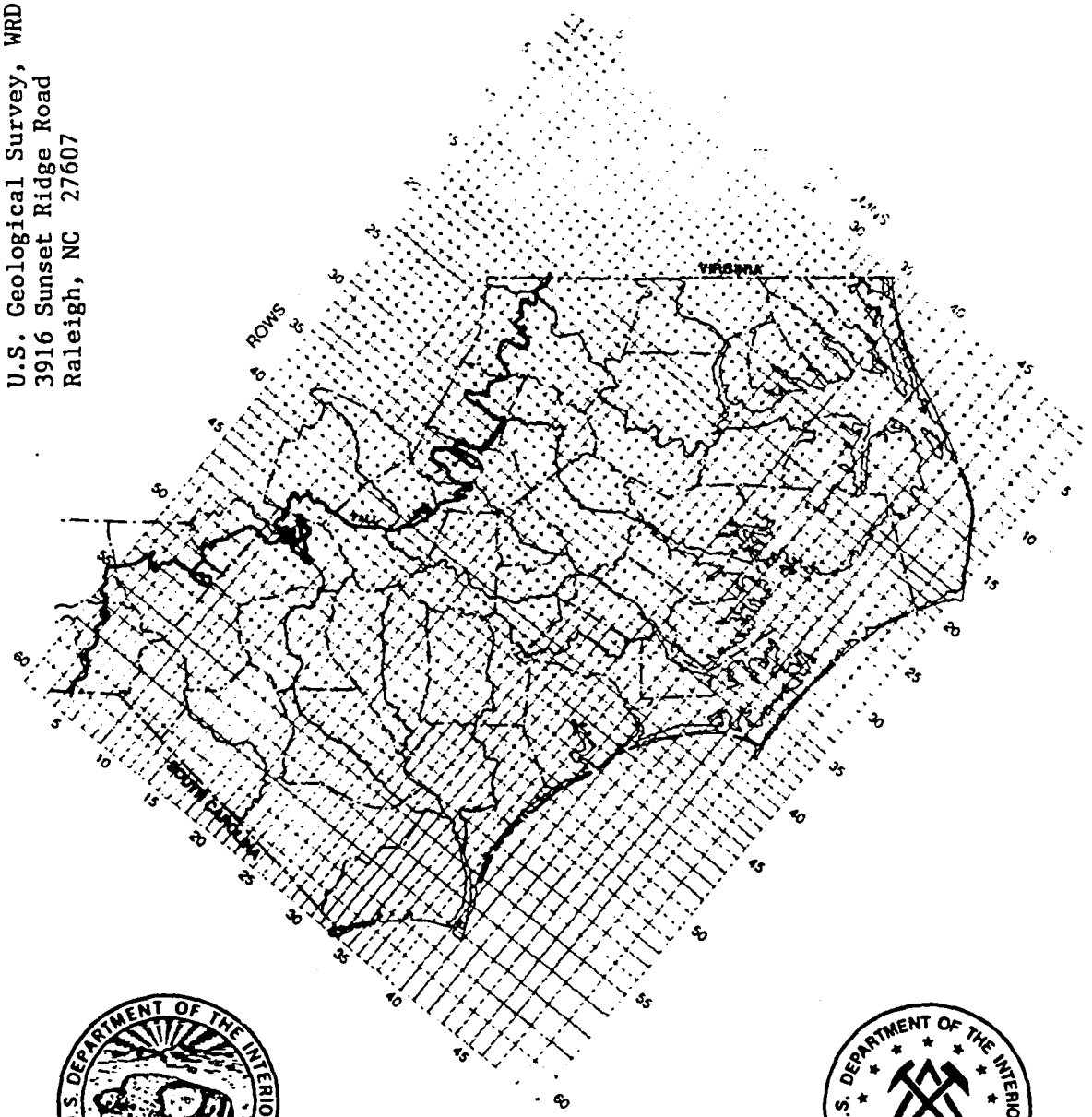

SIMULATION OF GROUND-WATER FLOW IN THE COASTAL PLAIN AQUIFER SYSTEM OF NORTH CAROLINA

By G.L. Giese, J.L. Eimers, and R.W. Coble

U.S. GEOLOGICAL SURVEY

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Raleigh, North Carolina

1991

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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Foreword

The Regional Aquifer System Analysis Program

The Regional Aquifer-System Analysis (RASA) program was started in 1978 after a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA program represents a systematic effort to study a number of the Nation's most important aquifer systems which, in aggregate, underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system, and of any changes brought about by human activities, as well as to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

CONVERSION FACTORS

The following factors may be used to convert the inch-pound units published in this report to the International System of Units (SI).

Multiply inch-pound unit	By	To obtain SI unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	.1894	meter per kilometer (m/km)
	Area	
square foot (ft^2)	.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4,047	square meter (m^2)
	Volume	
cubic yard (yd^3)	.7646	cubic meter (m^3)
acre-foot	1,233	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
gallon per day (gal/d)	3.785	liter per day (L/d)
million gallons per day (Mgal/d)	.04381	cubic meter per second (m^3/s)
	Velocity	
foot per second (ft/s)	.3048	meter per second (m/s)
mile per hour (mi/hr)	1.609	kilometer per hour (km/hr)
	Mass	
pound (lb avoirdupois)	.4536	kilogram (kg)
ton (short, 2,000 lbs)	.9072	tonne (t)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called, Sea Level Datum of 1929.

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SIMULATION OF GROUND-WATER FLOW IN THE COASTAL PLAIN AQUIFER SYSTEM OF NORTH CAROLINA

By G.L. Giese, J.L. Eimers, and R.W. Coble

ABSTRACT

A three-dimensional finite-difference digital model was used to simulate ground-water flow in the 25,000 square-mile aquifer system of the North Carolina Coastal Plain. The model was developed from a hydrogeologic framework that is based on an alternating sequence of 10 aquifers and 9 confining units, which comprise a seaward-thickening wedge of sediments that form the Coastal Plain aquifer system in the State of North Carolina.

The model was calibrated by comparing observed and simulated water levels. The model calibration was achieved by adjusting model parameters, primarily transmissivity of aquifers and leakance of confining units, until differences between observed and simulated water levels were within acceptable limits, generally within 15 feet. The maximum transmissivity of an individual aquifer in the calibrated model is 200,000 feet squared per day in a part of the Castle Hayne aquifer, which is composed predominately of limestone. The maximum simulated vertical hydraulic conductivity in a confining unit was 2.5 feet per day in a part of the confining unit overlying the upper Cape Fear aquifer. The minimum value was 4.1×10^{-6} feet per day in part of the confining unit overlying the lower Cape Fear aquifer. Analysis indicated the model is highly sensitive to changes in transmissivity and leakance near pumping centers; away from pumping centers, the model is only slightly sensitive to changes in transmissivity but is moderately sensitive to changes in leakance.

Recharge from precipitation to the surficial aquifer ranges from about 12 inches per year in areas having clay at the surface to about 20 inches per year in areas having sand at the surface. Most of this recharge moves laterally to streams, with only about 1 inch per year moving downward to the confined parts of the aquifer system. Under predevelopment conditions, the confined aquifers were generally recharged in updip interstream areas and discharged through streambeds and in downdip coastward areas. Hydrologic

analysis of the flow system using the calibrated model indicated that, because of ground-water withdrawals, areas of ground-water recharge have expanded and encroached upon some major stream valleys and into coastal areas. Simulations of pumping conditions indicate that by 1980 large parts of the former coastal discharge areas had become areas of potential or actual recharge.

Ground-water level declines, which are the result of water taken from storage, are extensive in some areas and minimal in others. Hydraulic head declines of more than 135 feet have occurred in the northern Coastal Plain since 1940 primarily due to withdrawals in the Franklin area in Virginia. Declines of ground-water levels greater than 110 feet have occurred in aquifers in the central Coastal Plain due to combined effects of pumpage for public and industrial water supplies. Water-level declines exceeding 100 feet have occurred in the Beaufort County area because of withdrawals for a mining operation and water supplies for a chemical plant. Head declines have been less than 10 feet in the shallow surficial and Yorktown aquifers and in the updip parts of the major confined aquifers distant from areas of major withdrawals. In 1980 contribution from aquifer storage was 14 cubic feet per second, which is about 4.8 percent of pumpage and about 0.05 percent of ground-water recharge.

A water-budget analysis using the model simulations indicates that much of the water removed from the ground-water system by pumping ultimately is made up by a reduction in water leaving the aquifer system, which discharges to streams as base flow. The reduction in stream base flow was 294 cubic feet per second in 1980 and represents about 1.1 percent of the ground-water recharge. The net reduction to streamflow is not large, however, because most pumped ground water is eventually discharged to streams. In places, such as at rock quarries in Onslow and Craven Counties, water is lost from streams to recharge the water-table aquifer. In simulations for the period 1980-2000, assuming a 3-percent increase in pumpage per year since 1980, such induced infiltration increased about seven-fold from about 6 to 42 cubic feet per second.

INTRODUCTION

The North Carolina Coastal Plain (fig. 1) covers an area of 25,000 mi^2 (square miles) in the eastern part of the State. This area includes about 47 percent of the State and encompasses all or parts of 47 counties.

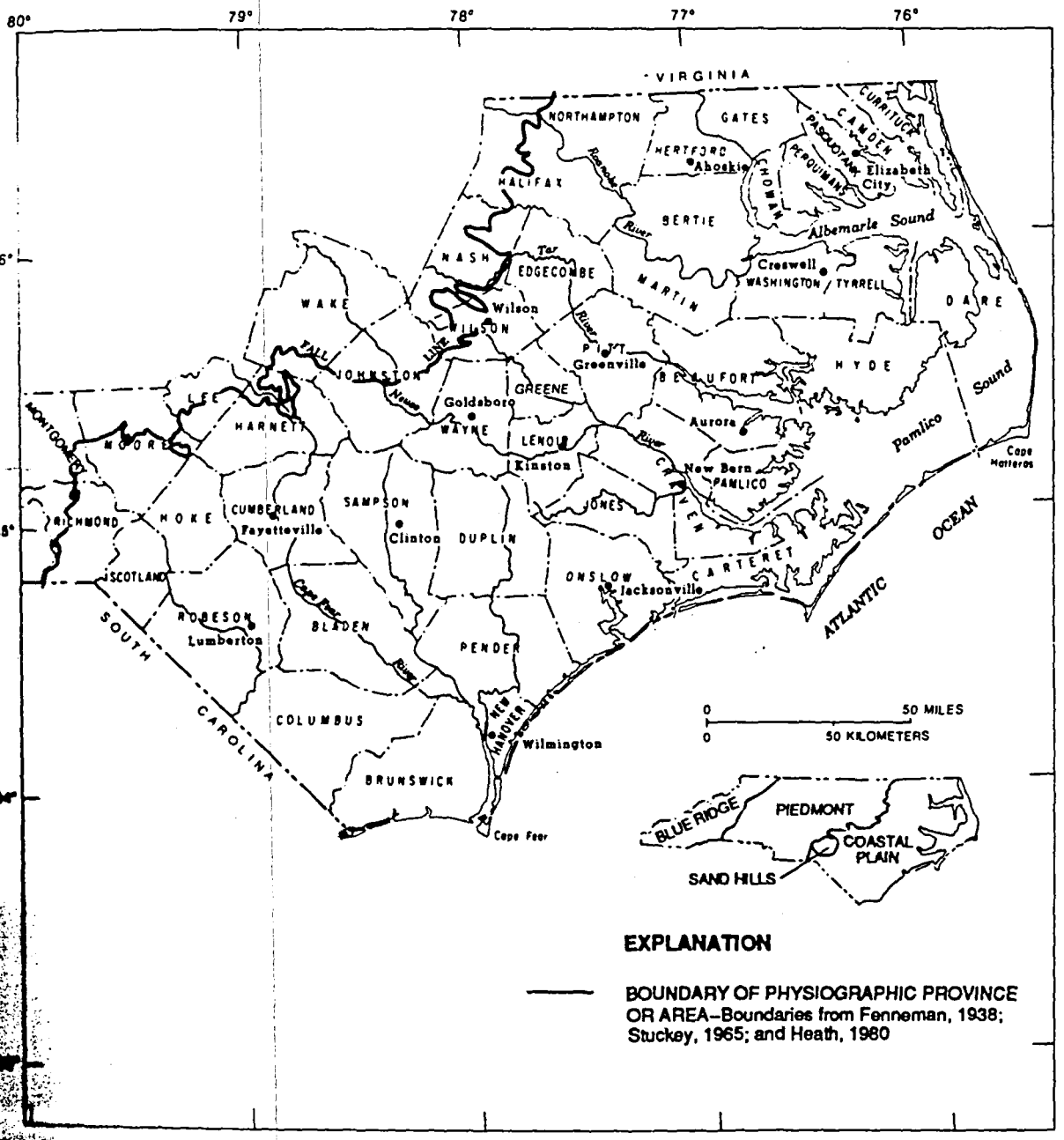


Figure 1.--Study area of the North Carolina Coastal Plain aquifer system.

The western boundary of the study area coincides roughly with the boundary between Fenneman's (1938) Coastal Plain and Piedmont province and is delineated by the Fall Line. The northern and southern boundaries coincide with the Virginia and South Carolina borders, respectively. The eastern boundary, though not shown in figure 1, is defined as the seaward limit of ground water that has a dissolved chloride concentration of 10,000 mg/L (milligrams per liter).

The North Carolina Coastal Plain is an eastward-dipping and thickening sequence of sand, silt, clay, and limestone. Beds primarily composed of sand or limestone comprise aquifers, and beds largely consisting of clay and silt are confining units. This sequence of aquifers and confining units is considered to function as a single aquifer system.

Water derived from aquifers of the North Carolina Coastal Plain aquifer system constitutes the major source of water for municipal and domestic water supplies; it is also an important source of water for industrial and agricultural purposes. Total ground-water withdrawal in the North Carolina Coastal Plain for 1980 is estimated at more than 250 Mgal/d (million gallons per day). However, this pumpage of ground water, both in the North Carolina Coastal Plain and in adjacent States, has led to several hydrogeologic concerns, including lowering of ground-water levels in some areas, reduction of base flow to streams, creation of the potential for land subsidence, and movement of saltwater and contaminated water into the areas used for water supplies.

Effective planning for use of ground water in the Coastal Plain is needed to provide future water-supply needs while minimizing potentially adverse effects of this development. Such planning requires a detailed qualitative and quantitative understanding of the functioning of the ground-water flow system, including the response of the aquifer system to existing and proposed pumping stresses. To help develop such understanding, a subregional investigation of the aquifer system of the North Carolina Coastal Plain was begun in 1979 as part of a larger regional study of the North Atlantic Coastal Plain aquifer system (fig. 2). Both studies are part of the U.S. Geological Survey's Regional Aquifer Systems Analysis (RASA) program. The regional RASA study covers about 50,000 mi^2 of the Coastal

Plain areas of New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina. Other subregional RASA studies were conducted in each of the other States, and all were coordinated at State lines. The broad objectives for all of the studies were similar--to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the aquifer system, and to develop capabilities that will be used to aid the effective management of ground-water resources.

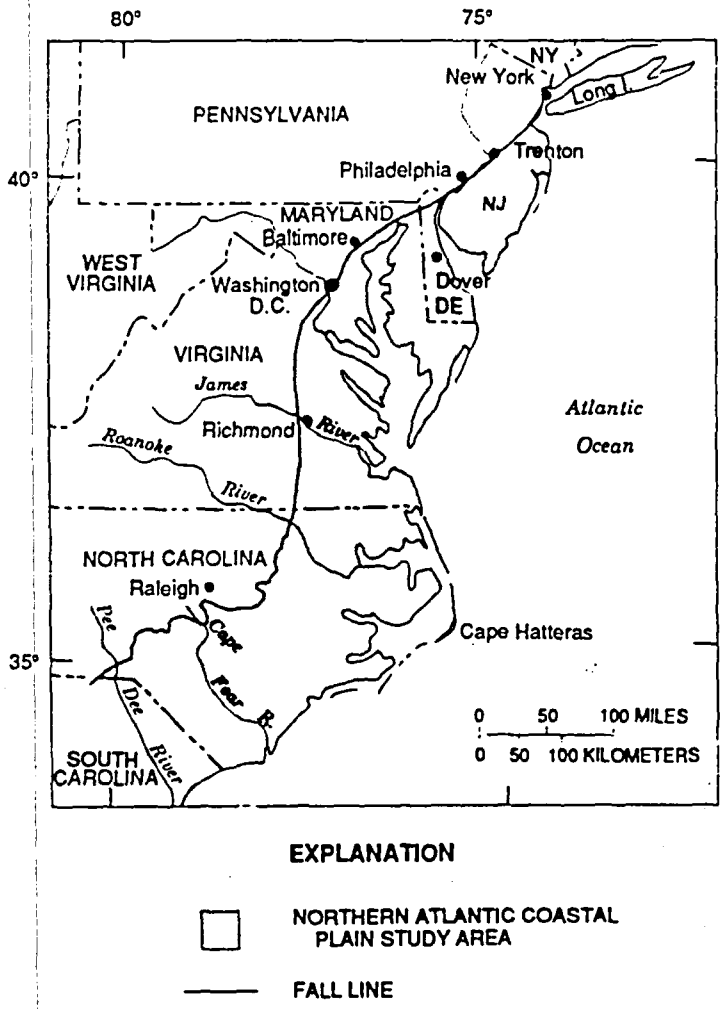


Figure 2.--The Northern Atlantic Coastal Plain study area (modified from Meisler, 1986).

The final results of the North Atlantic Coastal Plain RASA study are described in U.S. Geological Survey Professional Paper series 1404. This report is chapter M in the series. Other chapters that relate directly to this chapter are:

Chapter A. "The Regional Aquifer System Underlying the Northern Atlantic Coastal Plain in Parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York."

Chapter D. "The Occurrence and Geochemistry of Salty Ground Water in the Northern Atlantic Coastal Plain."

Chapter F. "Conceptualization and Analysis of Ground-Water Flow in the Coastal Plain Aquifers of Virginia and Parts of Maryland and North Carolina."

Chapter G. "Hydrogeologic Framework of the North Atlantic Coastal Plain in Parts of North Carolina, Virginia, Maryland, Delaware."

Chapter I. "Hydrogeologic Framework of the North Carolina Coastal Plain Aquifer System."

Chapter K. "Geohydrology and Simulation of Ground-Water Flow in the Northern Atlantic Coastal Plain Aquifer System."

Chapter L. "Geochemistry of the Northern Atlantic Coastal Plain."

Purpose and Scope

The purpose of this report is to describe the simulation of ground-water flow in the Coastal Plain of North Carolina for conditions prior to and after development of ground water. A finite-difference ground-water flow model was applied to 10 aquifers and intervening confining units, each of which covers all or part of the State's 25,000 mi^2 Coastal Plain. Discussions include modeling procedures and boundary conditions, calibration, sensitivity analysis, steady-state for prepumping conditions, and transient simulations for 1900-80 conditions.

Results of the simulations are discussed with respect to changes in ground-water flow as shown by changes in the water budget, potentiometric surface of each aquifer, and direction of ground-water flow vertically through the confining units. Results of a simulation for the year 2000 using an assumed constant increase in pumping of 3 percent per year from 1980 to 2000 at all 1980 pumping locations also are presented.

Methods of Investigation

This study was conducted in three stages. The first stage consisted of the development of a conceptual model of the ground-water flow system for

the North Carolina Coastal Plain. This conceptual model consists of the hydrogeologic framework of Winner and Coble (1989), estimates of aquifer and confining-unit properties, and general concepts as to the functioning of the system, including patterns of ground-water movement, nature of the system boundaries, and rates and locations of recharge and discharge.

The second stage of the study included the mathematical representation of the aquifer system. In this stage, elements of the conceptual model of the aquifer system were translated into numerical data sets suitable for manipulation in a mathematical-numerical model, which is a combination of a system of mathematical equations representing the behavior of the ground-water flow system and numerical procedures for solving the equations. A computer program described by Trescott (1975) and modified by Leahy (1982) was used to solve the governing equations of ground-water flow.

Simulated water levels resulting from model trials were compared with measured levels during the period 1900-80 to determine how realistically the digital model reproduced actual water levels. Model parameters were varied in order to improve the match between the observed and simulated water levels and to reduce errors in parameter estimates. When the model reproduced observed water levels within an acceptable range, the model was considered to be calibrated. For each trial set of model parameters, a series of three simulations was made (discussed in detail in the "Model Calibration" section of this report).

A sensitivity analysis was then performed on the calibrated model to determine the general degree of improvement of model parameter values as a result of the model calibration. The analysis consisted of evaluating the effect on model results caused by changing each of the model parameters. If model results showed little variation over a broad range of variation of a given parameter, then the model was said to be insensitive to that parameter, and it is not probable that the calibration process improved the estimates of the parameter. Conversely, if model results showed great sensitivity to a given parameter, then changes made in that parameter to improve agreement of model results with observed water levels likely resulted in improved estimates of that parameter. A computer printout of the model parameters used in the calibrated model is on file at the District

Office, U.S. Geological Survey, Water Resources Division, Raleigh, North Carolina.

The third stage of the study was hydrologic analysis of the aquifer system for predevelopment and development conditions. The analysis involved comparison of water levels in aquifers and vertical flow through confining units for the years 1900 (predevelopment) and 1980 (development). A predictive analysis was also done for the year 2000, assuming a 3-percent annual increase in pumping from 1980.

These three stages were largely, but not entirely, consecutive in time. For example, work done in digital model calibration at times revealed a need to revise previous concepts of the hydrogeologic framework. This, in turn, led to a revised digital model and affected the results of the hydrologic analysis.

Previous Investigations

Winner and Coble (1989) described the hydrogeologic framework for the North Carolina Coastal Plain, which is used and briefly described in this report. Several of the previous hydrogeologic investigations which have contributed significantly to knowledge of the hydrogeology of North Carolina Coastal Plain sediments are mentioned below; however, the reader is referred to the Winner and Coble report for a more complete review of these investigations.

Clark and others (1912) reported on the first comprehensive survey of the geology and ground-water resources of the North Carolina Coastal Plain. LeGrand (1964) presented a broad review of the hydrogeology of the Atlantic and Gulf Coastal Plains and discussed important hydrologic concepts related to the functioning of the ground-water reservoir throughout this large region. Brown, Miller, and Swain (1972) identified 17 chronostratigraphic units that are more or less continuous throughout the Coastal Plain from New York to North Carolina. On the basis of geophysical logs, driller logs, and well cuttings, lithofacies and indices of intrinsic permeability for each unit were mapped and estimated.

Other discussions of ground-water hydrology of multicounty areas in the North Carolina Coastal Plain are contained in Mundorff (1946), Brown (1959), LeGrand (1960), Schipf (1961), Blankenship (1965), Nelson (1964, 1976), Nelson and Barksdale (1965), Harris and Wilder (1966), DeWiest and others (1967), Floyd and Peace (1974), Peek (1977), and Narkunas (1980); these are included in "References" at the end of this report.

Publications describing simulation of ground-water flow in the Coastal Plain of North Carolina are limited. Cosner (1975) simulated ground-water flow in the Lower Cretaceous aquifer in southeastern Virginia, including parts of northeastern North Carolina, utilizing a finite-difference model. Sherwani (1973) developed a two-dimensional finite-difference model of the Castle Hayne aquifer in the Lee Creek area in Beaufort County, primarily as a tool for evaluating the effects of dewatering operations for phosphate mining on the potentiometric surface. Layne-Western Company (1983) developed a steady-state electric-analog model to simulate flow in the Cretaceous aquifer system of southeast Virginia and northeast North Carolina.

Acknowledgments

Data relating to the development of the hydrogeologic framework and conceptualization of the flow system were furnished by personnel in the Groundwater Section, Division of Environmental Management, in the North Carolina Department of Environment, Health, and Natural Resources (EHNR). The specific individuals deserving special thanks are Perry F. Nelson, William Jeter, Carl Bailey, Richard Shiver, Edward Berry, William Bright, and L.A. Register.

CONCEPTUALIZATION OF THE AQUIFER SYSTEM

In this report, the conceptual model of the ground-water flow system of the North Carolina Coastal Plain is presented in a partly quantitative fashion and includes general ideas about the functioning of the aquifer system, particularly the ways recharge and discharge occur, how water moves through the system, an understanding of the physical environment through which flow occurs, and the nature of the system boundaries.

The source of water for the aquifer system is recharge from precipitation to the surficial aquifer, which, for the most part, is under water-table conditions. Figure 3 illustrates a generalized water budget for a typical location in the North Carolina Coastal Plain (Wilder and others, 1978). The budget shown in figure 3 represents predevelopment (steady-state) conditions in which water entering the aquifer system is equal to the water leaving it. Precipitation is about 50 in/yr (inches per year). Of this amount, about 33 in. (inches) is lost through evapotranspiration, about 5 in. is lost through overland runoff, and about 12 in. infiltrates to the water table (fig. 3). Of this 12 in., about 11 in. moves laterally to streams. In most places, about 1 in. or less moves vertically down through confining units to the confined ground-water flow system. Water generally moves down into the confined aquifers in interstream areas. It generally moves up from the confined aquifers into streambeds of large rivers and into sounds and the ocean in downdip coastward areas (fig. 4).

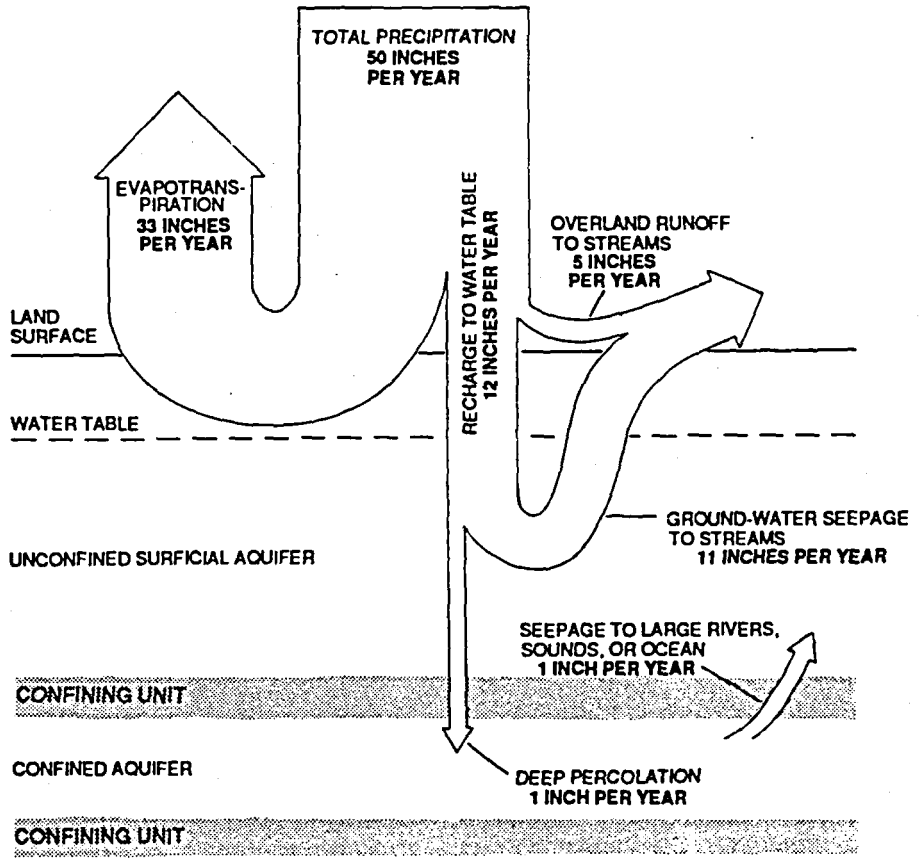


Figure 3.--Typical annual water budget for the North Carolina Coastal Plain hydrogeologic system (modified from Wilder and others, 1978).

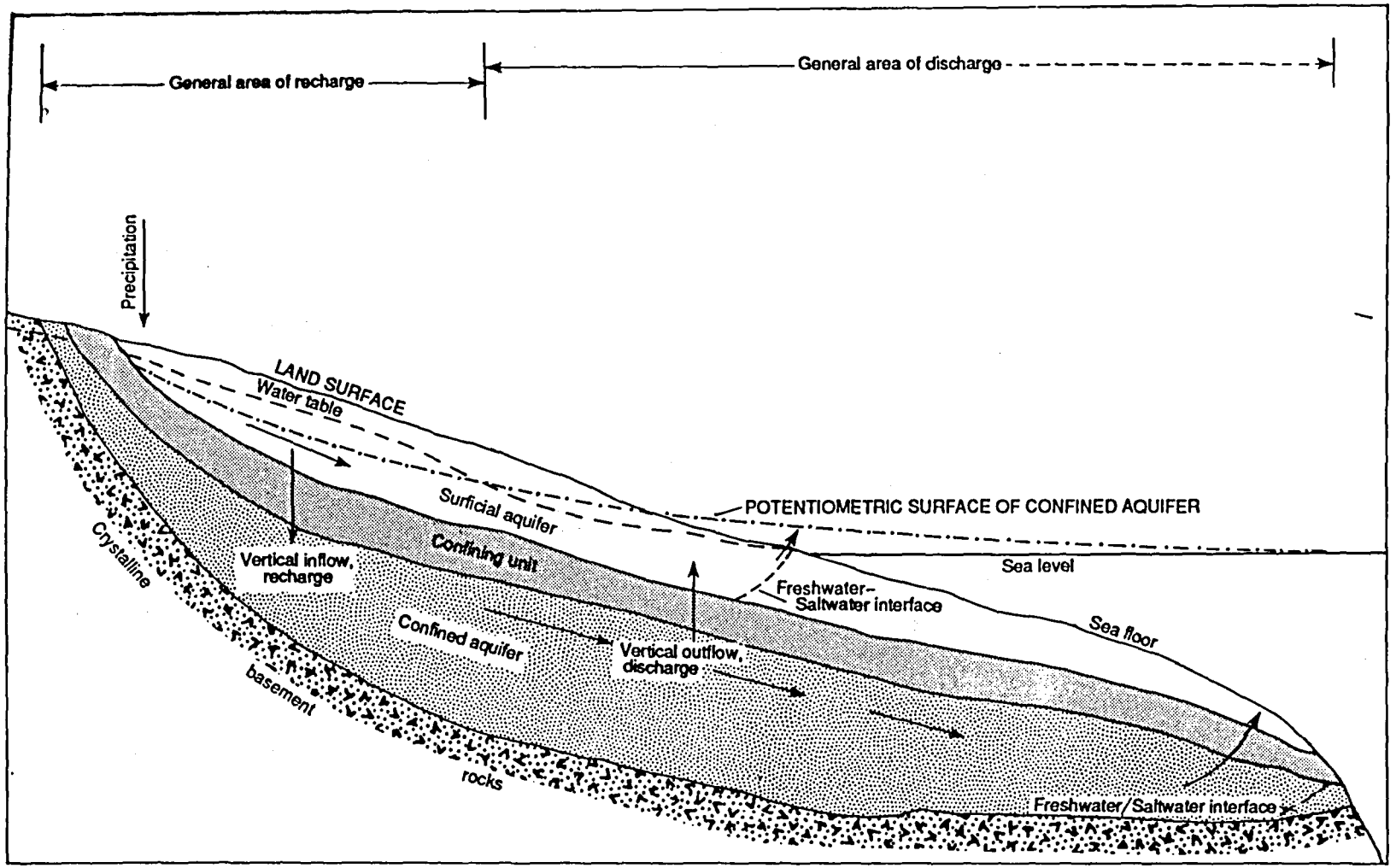


Figure 4.--Idealized hydrogeologic cross section showing features of the ground-water flow system.

For modeling purposes, flow through confining units is considered to be primarily vertical as shown in figure 4, and flow through aquifers is considered to be horizontal. The unconsolidated Coastal Plain aquifer system is underlain by crystalline basement rocks of low permeability. It is assumed that there is little significant exchange of water between the basement rocks and the Coastal Plain aquifers; therefore, the top of the basement rocks is considered as a no-flow boundary for the aquifer system.

Fresh ground water in Coastal Plain aquifers usually grades into saltwater near the coastline. At some point in each aquifer, the effect of saltwater density balances the freshwater head potential so that ground-water movement becomes insignificant. In this study, this is assumed to occur at the point where the chloride concentration in ground water is 10,000 mg/L. The seaward limit of ground water containing less than 10,000 mg/L of chloride, as given by Meisler (1981), is considered as a no-flow boundary.

The hydrogeologic framework of Winner and Coble (1989) for the Coastal Plain of North Carolina, outlined in the following section of the report, served as the primary basis for the initial numerical representation of the flow system in the digital model. Other aspects of the conceptual model of the flow system, including recharge and discharge, movement of water through the system, and the nature of the system boundaries are discussed later in the report as they relate to the digital flow model.

HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework presented by Winner and Coble (1989) consists of 10 aquifers and 9 confining units (table 1). However, these hydrogeologic units do not occur everywhere in the North Carolina Coastal Plain. Equivalent hydrogeologic units for neighboring States are also shown in table 1, although some of these are not present at the respective borders with North Carolina.

For the convenience of constructing a digital model of the ground-water flow system, the hydrogeologic units are sometimes abbreviated using a letter and number as shown in table 1. Aquifers (A) are numbered from the lowest unit upward; confining unit (CU) designations are taken from the

Table 1.--North Carolina, South Carolina, and Virginia Coastal Plain hydrogeologic units
(modified from Winner and Coble, 1989)

Virginia hydrogeologic units[1/]		North Carolina hydrogeologic units and model layer number		South Carolina hydrogeologic units[2/]
Columbia aquifer		Surficial aquifer A10		Surficial aquifer
Yorktown confining unit		Yorktown confining unit CU9		Hydrogeologic units equivalent to North Carolina units not present in northeastern South Carolina [3/]
Yorktown-Eastover aquifer		Yorktown aquifer A9		
St. Marys confining unit		Pungo River confining unit CU8		
St. Marys-Choptank aquifer		Pungo River aquifer A8		
Calvert confining unit		Castle Hayne confining unit CU7		
Chickahominy-Piney Point aquifer		Castle Hayne aquifer A7		
Nanjemoy-Marlboro Clay confining unit		Beaufort confining unit CU6		
Aquia aquifer		Beaufort aquifer A6		
Brightseat confining unit	4/			
Brightseat aquifer				
North Carolina units not present in Virginia		Peedee confining unit CU5		
		Peedee aquifer A5		
		Black Creek confining unit CU4		
		Black Creek aquifer A4		Black Creek aquifer
				Unnamed confining unit
				Middendorf aquifer
Upper Potomac confining unit		Upper Cape Fear conf. unit CU3		Unnamed confining unit
Upper Potomac aquifer		Upper Cape Fear aquifer A3		Cape Fear aquifer
Middle Potomac confining unit		Lower Cape Fear conf. unit CU2		
Middle Potomac aquifer		Lower Cape Fear aquifer A2		
Lower Potomac confining unit		Lower Cretaceous conf. unit CU1	5/	
Lower Potomac aquifer		Lower Cretaceous aquifer A1		

1/ Meng and Harsh (1988).

2/ Southeastern Coastal Plain aquifer system (Aucott and others, 1987).

3/ Tertiary equivalents (Floridan and Tertiary sand aquifers) are present in the central and southern South Carolina Coastal Plain (Aucott and others, 1987).

4/ Restricted to northern Virginia; not present along North Carolina-Virginia boundary.

5/ Restricted to northern North Carolina; not present along North Carolina-South Carolina boundary.

aquifers they overlie. Thus, aquifer A1 is the lowermost aquifer and the confining unit overlying it is CU1. These designations are referred to frequently in this report.

Selected hydrogeologic sections were adopted from Winner and Coble (1989) to show the distribution of aquifers and confining units throughout the North Carolina Coastal Plain (figs. 5 through 9). The idealized sections show the thickening, thinning, and pinch-outs typical of these hydrogeologic units in the study area. Confining units are considered to terminate at the limit of the underlying aquifer. These relations are built into the modeling process, and the reader is referred to Winner and Coble (1989) for detailed geologic and hydrologic descriptions. Brief descriptions of each hydrogeologic unit are presented in this section.

Surficial Aquifer (A10)

The surficial aquifer (A10) overlies all of the North Carolina Coastal Plain (fig. 1) and consists of fine sand, silt, clay, shell, and peat beds. Scattered deposits of coarser-grained sediments in the unit occur in relict beach ridges or in alluvium. Throughout the western and central parts of the Coastal Plain, the thickness of the surficial aquifer ranges from a few feet to about 30 ft (feet); however, the aquifer thickens eastward and is more than 200 ft thick in the vicinity of the Outer Banks. The sediments of the surficial aquifer are primarily of post-Yorktown age, but are not restricted to a single geologic unit in terms of age or lithology (Winner and Coble, 1989).

The surficial aquifer (A10) directly overlies most of the confined aquifers at one place or another and exchanges water with them either directly or through an intervening confining bed. The surficial aquifer receives direct recharge from precipitation and is the source of water for the deeper confined aquifers and base flow to streams. The amount of recharge from precipitation varies areally from about 12 to 20 in/yr, depending on the clay content of the soils. Winner and Coble (1989) estimated the average horizontal hydraulic conductivity of the surficial aquifer to be 29 ft/d (feet per day). A more detailed description of movement of water within the surficial aquifer is given in the section entitled "Model Input."

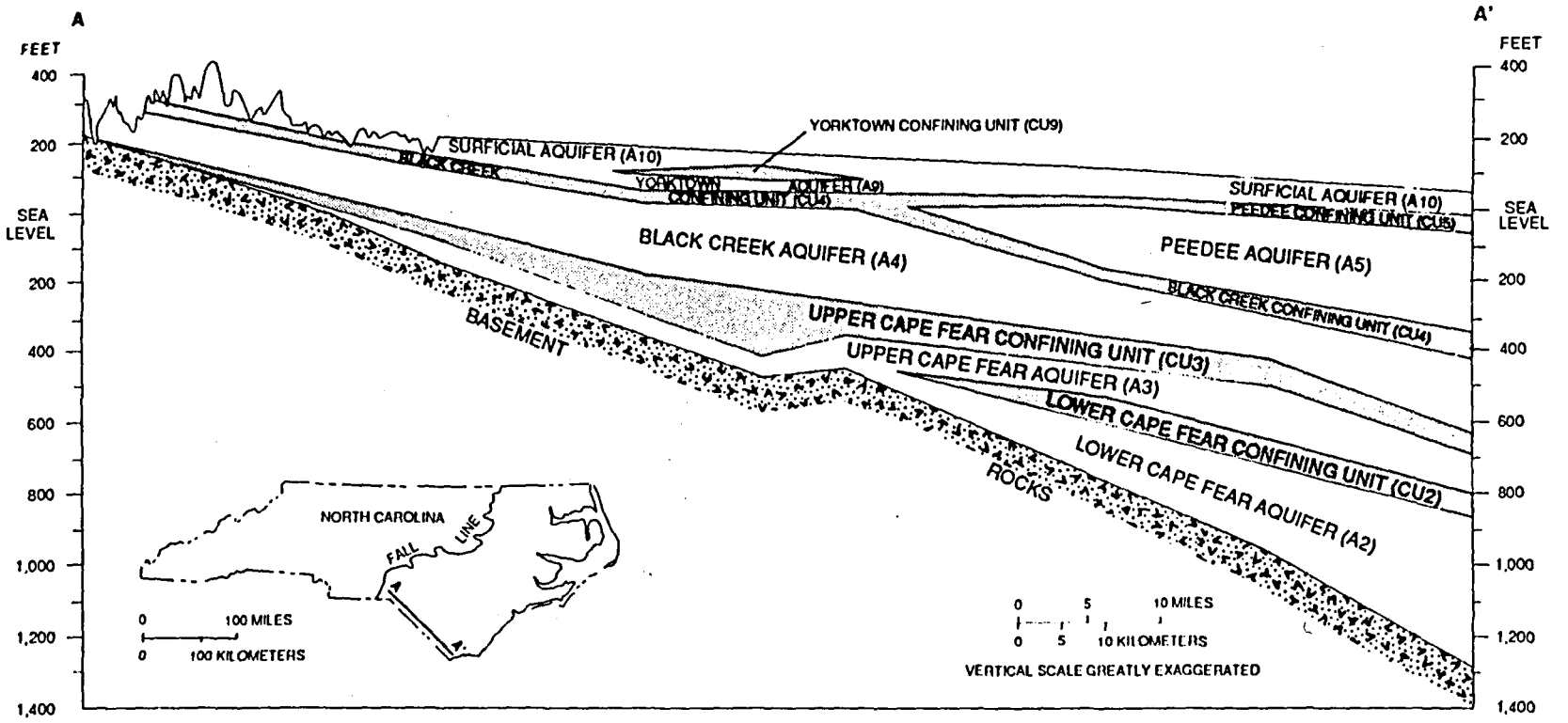


Figure 5.--Hydrogeologic section A-A′ from Richmond County to Brunswick County (modified from Winner and Coble, 1989).

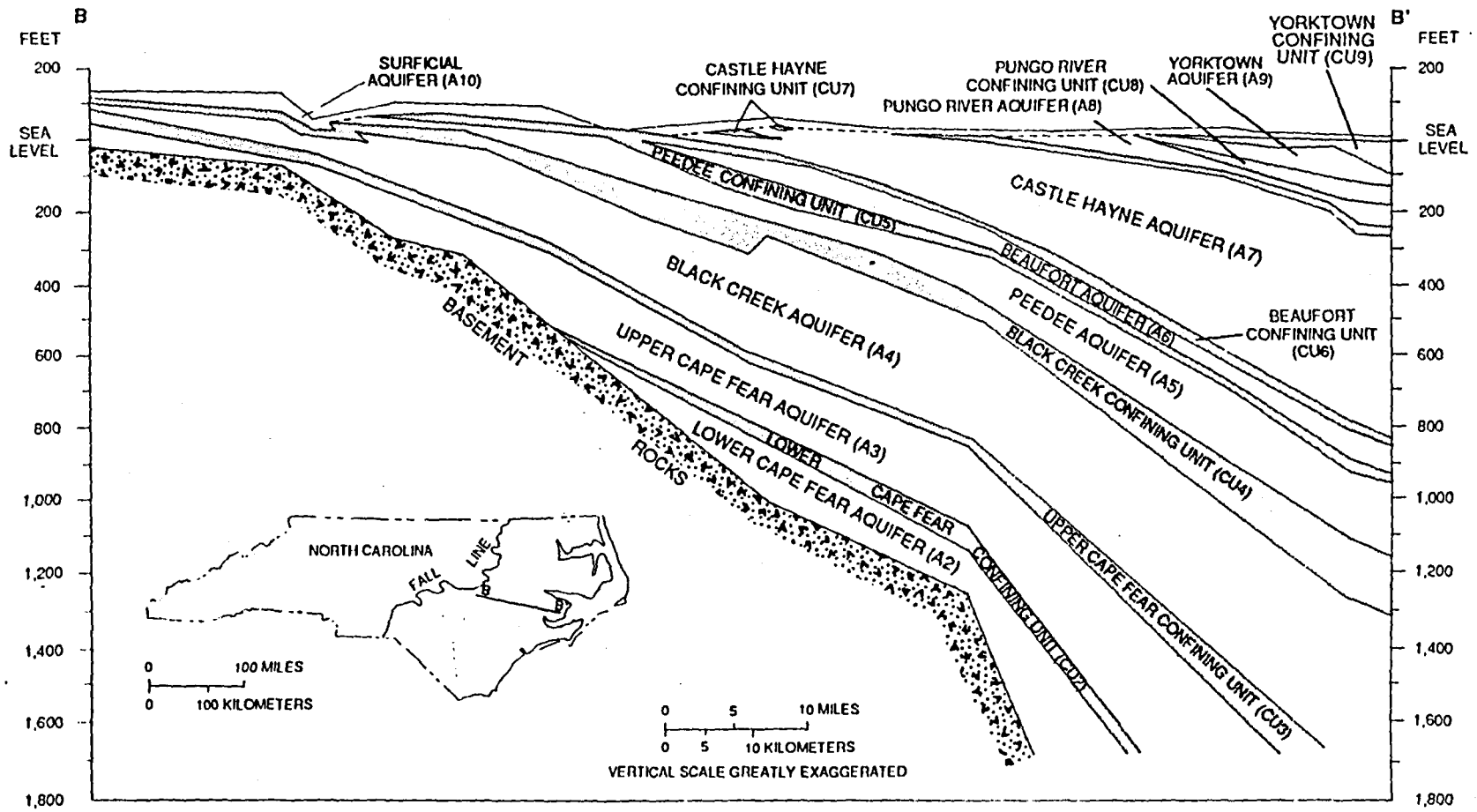


Figure 6.--Hydrogeologic section B-B′ from Johnston County to Pamlico County (modified from Winner and Coble, 1989).

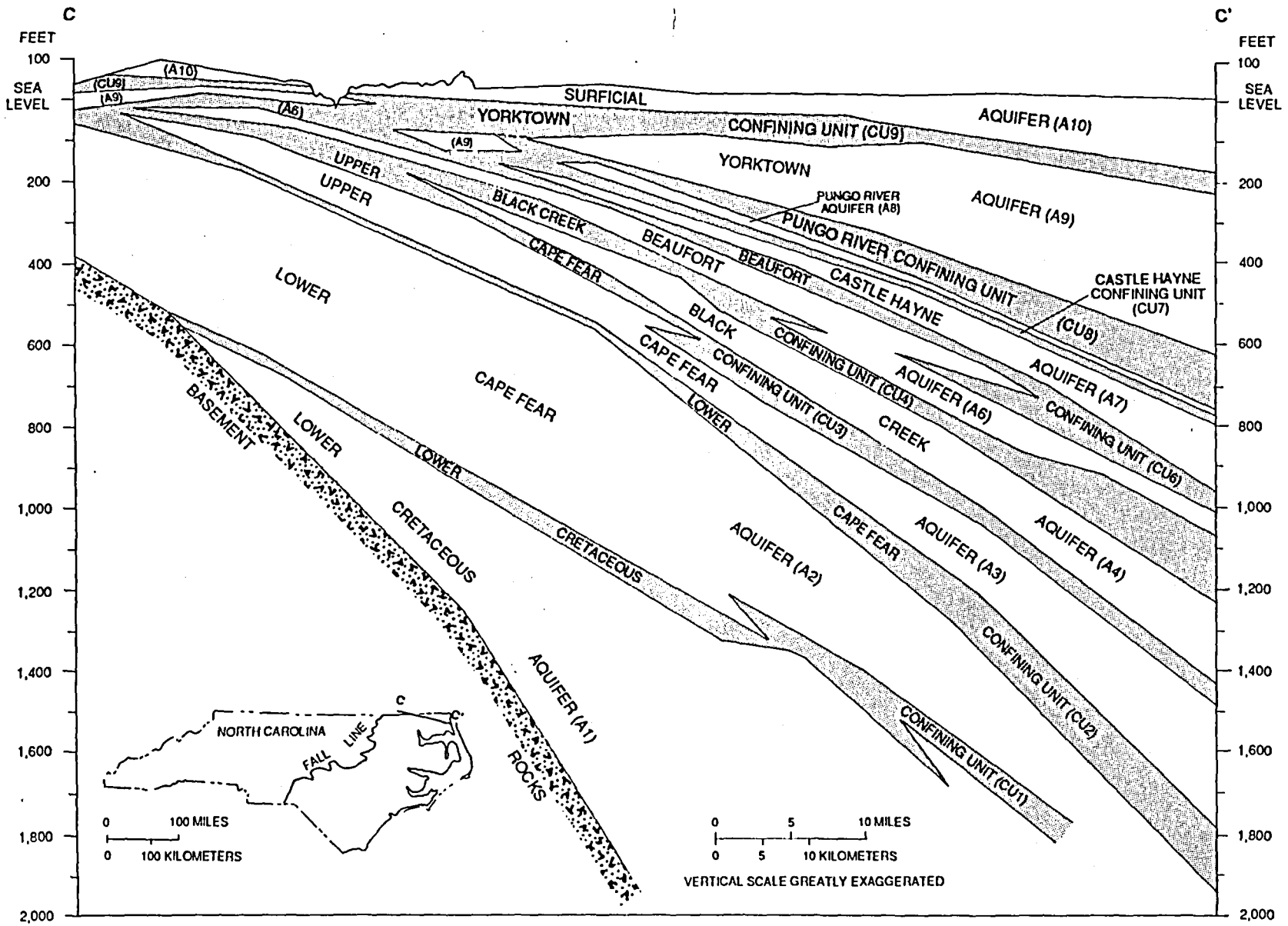


Figure 7.--Hydrogeologic section C-C′ from Southampton County, Virginia, to Currituck County, North Carolina (modified from Winner and Coble, 1989).

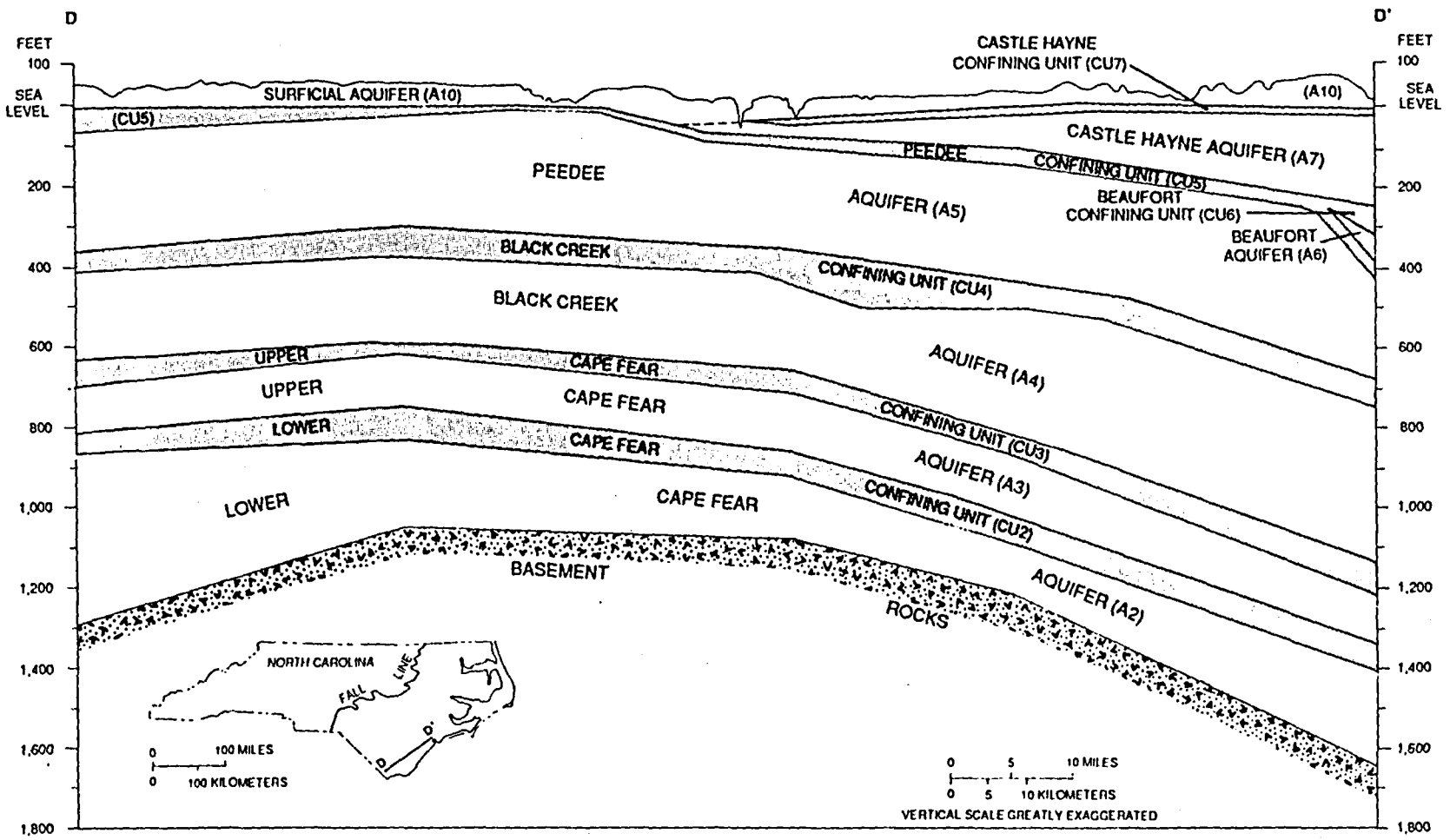


Figure 8.--Hydrogeologic section D-D' from Brunswick County to Onslow County (modified from Winner and Coble, 1989).

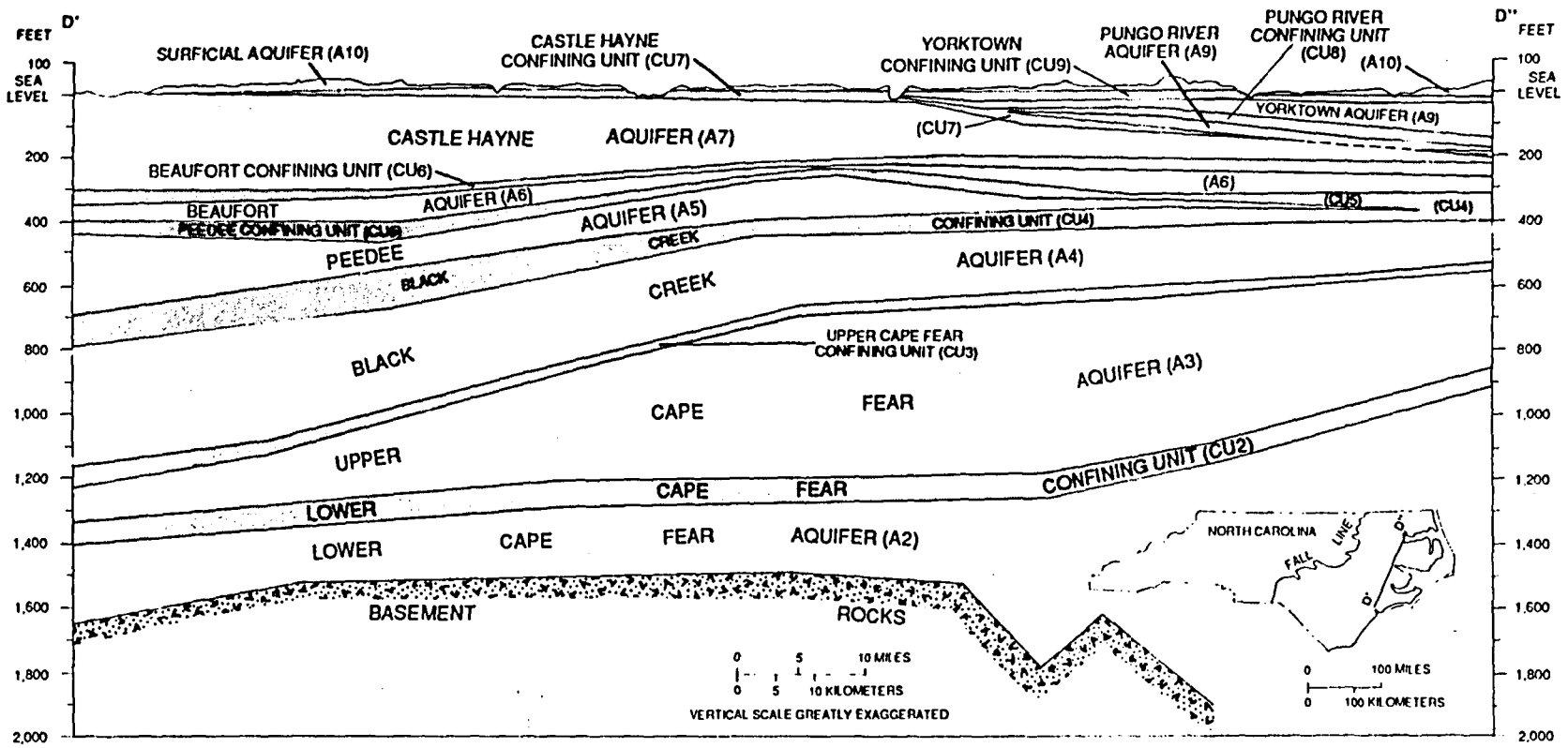


Figure 9.--Hydrogeologic section D'-D'' from Onslow County to Chowan County (modified from Winner and Coble, 1989).

Yorktown Aquifer (A9) and Overlying Confining Unit (CU9)

The Yorktown aquifer (A9), is equated with the older beds of the Pliocene Yorktown Formation of Clark and others (1912) and extends throughout the northern half of the Coastal Plain (fig. 10) from the Fall Line, where it overlies crystalline rocks similar to those in the Piedmont, eastward to beyond the coast. The Yorktown aquifer is largely composed of fine sand, silty and clayey sand, and sand with shells and shell beds, with some limestone and coarse sand beds also present. In the western Coastal Plain, the aquifer is relatively thin, less than 20 ft thick in many places, and has been cut into or eroded away by the larger streams flowing across the area. In Dare County, the Yorktown aquifer attains its maximum thickness of over 300 ft.

The Yorktown aquifer (A9) does not extend into the southern half of the Coastal Plain, except for a small area in Robeson County (fig. 10) which is the largest of a number of outliers shown by Brown and others (1972, pl. 21). Figure 10 also shows the areal extent of aquifers that underlie the Yorktown aquifer. The surficial aquifer (A10) overlies the Yorktown aquifer everywhere.

The estimated horizontal hydraulic conductivity of the Yorktown aquifer (A9) ranges from 19 to 33 ft/d and averages about 21 ft/d, based on aquifer tests and lithologic- and geophysical-log data from 52 wells and test holes (Winner and Coble, 1989).

The Yorktown confining unit (CU9) overlying the Yorktown aquifer is comprised of the youngest clay beds of the Yorktown Formation in most places, but locally may include clay beds of Pleistocene or Holocene age. Its thickness averages about 25 ft, ranging from less than 10 up to 50 ft thick. It is composed largely of clay and sandy clay that locally includes beds of fine sand or shell. The Yorktown confining unit generally is considered to extend only as far as the Yorktown aquifer, even though stratigraphically equivalent beds may continue beyond the aquifer limits.

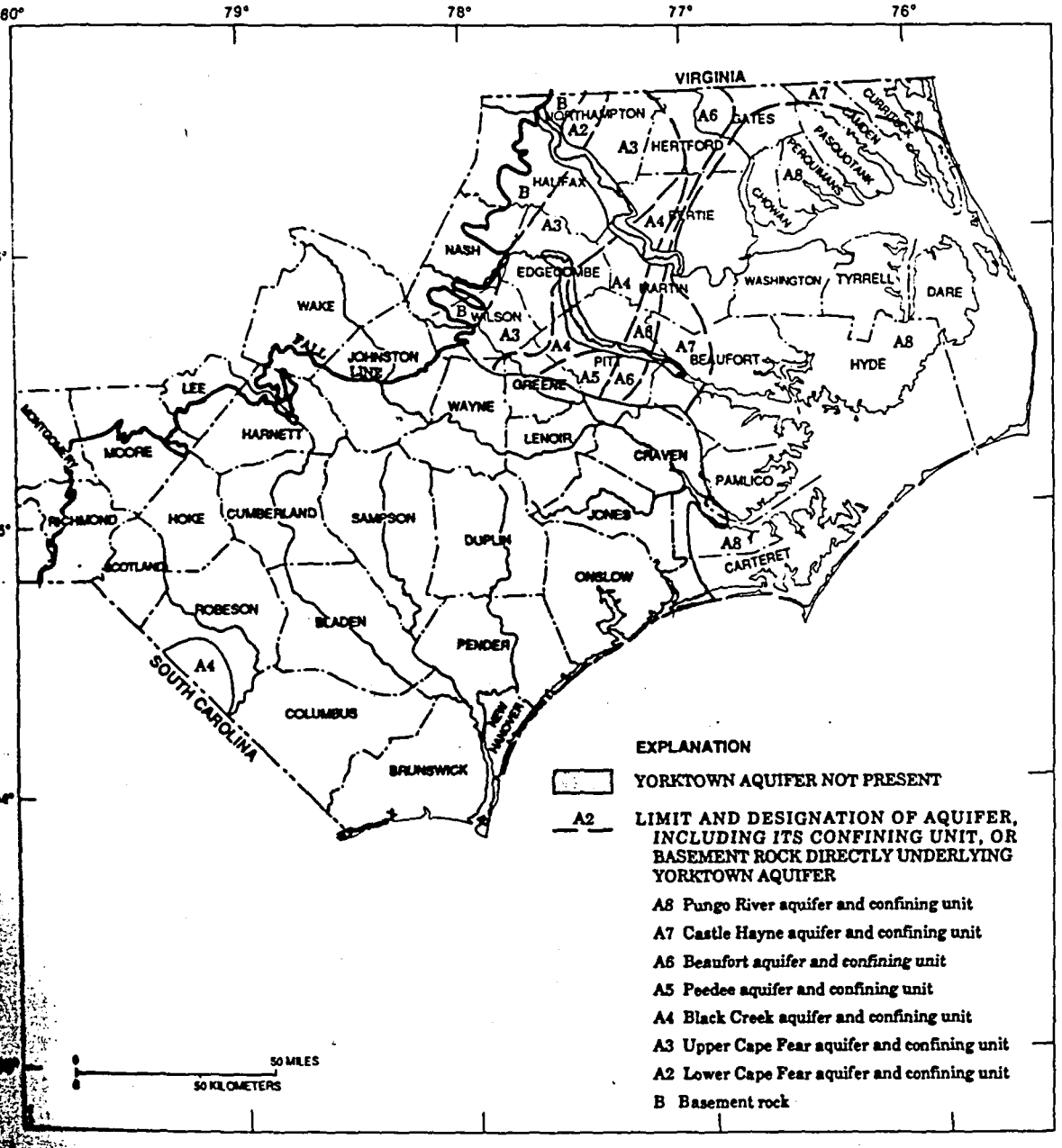


Figure 10.--Areal extent of the Yorktown aquifer (A9) and underlying aquifers or basement rock (modified from Winner and Coble, 1989).

Pungo River Aquifer (A8) and Overlying Confining Unit (CU8)

The Pungo River aquifer (A8) consists of the permeable part of the Pungo River Formation of lower and middle Miocene age, described in detail by Kimrey (1965). The Pungo River aquifer is composed of fine to medium marine sands with considerable phosphate content. Average estimated horizontal hydraulic conductivity based on analysis of geophysical logs is 33 ft/d, according to Winner and Coble (1989). Shells and other fossils are present throughout the aquifer; occasionally, beds of limestone and coarse sand are found.

The Pungo River aquifer (A8) is thinnest near its western and northern limits, where its thickness averages about 15 ft. The aquifer dips eastward and thickens to more than 200 ft in the vicinity of the Outer Banks where the top is more than 700 ft below sea level. The aquifer is overlain everywhere by aquifers A9 or A10 (fig. 11), except where it is exposed in an open-pit phosphate mine in Beaufort County. The Pungo River aquifer is underlain everywhere by the Castle Hayne aquifer (A7).

The Pungo River confining unit (CU8) is formed by the upper clay beds of the Pungo River Formation and contiguous clays of the lowermost Yorktown Formation. The confining unit ranges in thickness from less than 10 ft near the western margin to about 150 ft beneath Currituck County, with an average thickness of nearly 55 ft. For most of the area, the confining unit is composed of nearly uniform clay containing less than 10 percent sand.

Castle Hayne Aquifer (A7) and Overlying Confining Unit (CU7)

The Castle Hayne aquifer (A7) is delineated as those calcareous sediments of Eocene age that are equated with the Castle Hayne Limestone and the Trent Formation of former usage of Clark and others (1912). Also included in this aquifer are rocks of Oligocene age, now designated River Bend Formation, overlying the Castle Hayne (Brown and others, 1972), which are lithologically identical and hydraulically connected to the Castle Hayne Limestone. The basal part of the aquifer may include older contiguous permeable units in local areas. The areal extent of this aquifer is shown in figure 12, which also shows the extent of overlying aquifers.

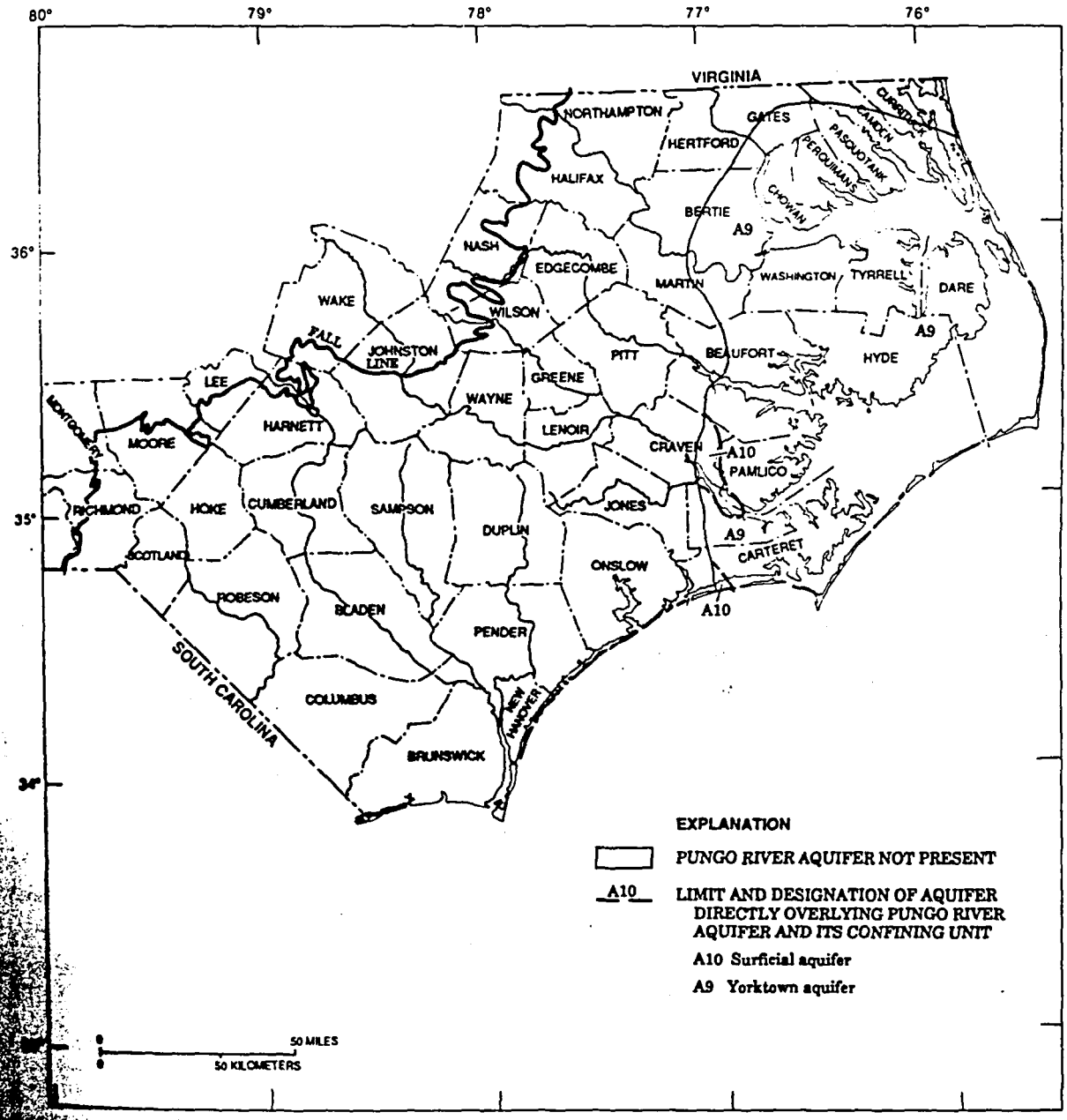


Figure 11.--Areal extent of the Pungo River aquifer (A8) and overlying aquifers (modified from Winner and Coble, 1989).

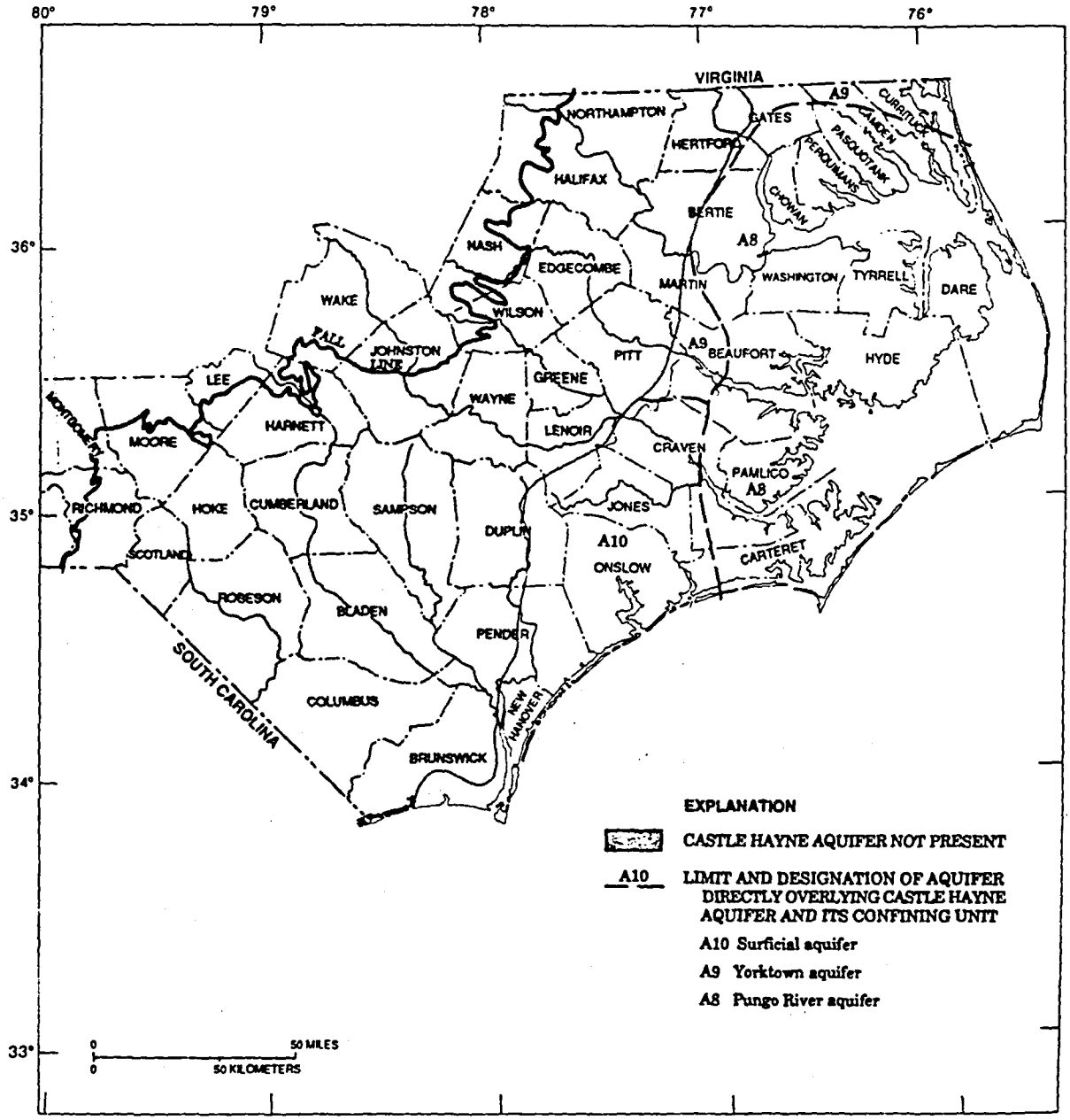


Figure 12.--Areal extent of the Castle Hayne aquifer (A7) and overlying aquifers (modified from Winner and Coble, 1989).

The Castle Hayne aquifer (A7) is composed of limestone, sand, and minor amounts of clay deposited under marine conditions. Limestone may occur as shell limestone, dolomitic limestone, and sandy limestone ranging from loosely consolidated to hard and recrystallized. Along the western margin, the aquifer occurs near land surface from New Hanover County to Craven County. Eastward, the aquifer thickens to more than 950 ft in Carteret County and to nearly 1,200 ft beneath Cape Hatteras (Brown, 1958, fig. 4). In the area north of Albemarle Sound, limestone beds are thin to nonexistent, and the sediments contain more clay. The thickness of the unit averages about 50 ft between Bertie and Currituck Counties but reaches a maximum of 115 ft in Currituck County.

The Castle Hayne aquifer (A7) is the most productive aquifer in North Carolina due to its thickness and high percentage of permeable limestone and sand. On the basis of aquifer tests and lithologic and geophysical log data, the hydraulic conductivity of the Castle Hayne aquifer ranges from about 15 ft/d, where it is composed of fine sand, to about 200 ft/d where the bulk of the aquifer is porous limestone.

The thickness of the Castle Hayne confining unit (CU7) averages only about 10 ft; it exceeds 25 ft only in Gates County along the Virginia border, in eastern Pamlico and Carteret Counties, and in two small areas along the western limit of the Castle Hayne aquifer (A7). The confining unit is composed of beds of clay, sandy clay, and clay with sandy streaks that are part of the Pungo River Formation, the Yorktown Formation, or younger clays. The confining unit is missing in several stream valleys south of Craven County and in two areas in the northeastern Coastal Plain. In addition to being thinner than most of the other confining units, the Castle Hayne confining unit contains more sand; thus, it is relatively permeable and allows significant vertical leakage between the Castle Hayne and overlying aquifers.

The Castle Hayne aquifer (A7) and confining unit (CU7) are directly overlain by the Pungo River aquifer (A8) throughout most of its northern and eastern area (fig. 12), whereas to the south, the Castle Hayne is overlain by the Yorktown and surficial aquifers (A9 and A10). The Castle Hayne is directly underlain by the Beaufort aquifer (A6) and confining unit (CU6) northeast of Jones and Onslow Counties and by the Peedee aquifer (A5) and confining unit (CU5) south of these counties (fig. 13).

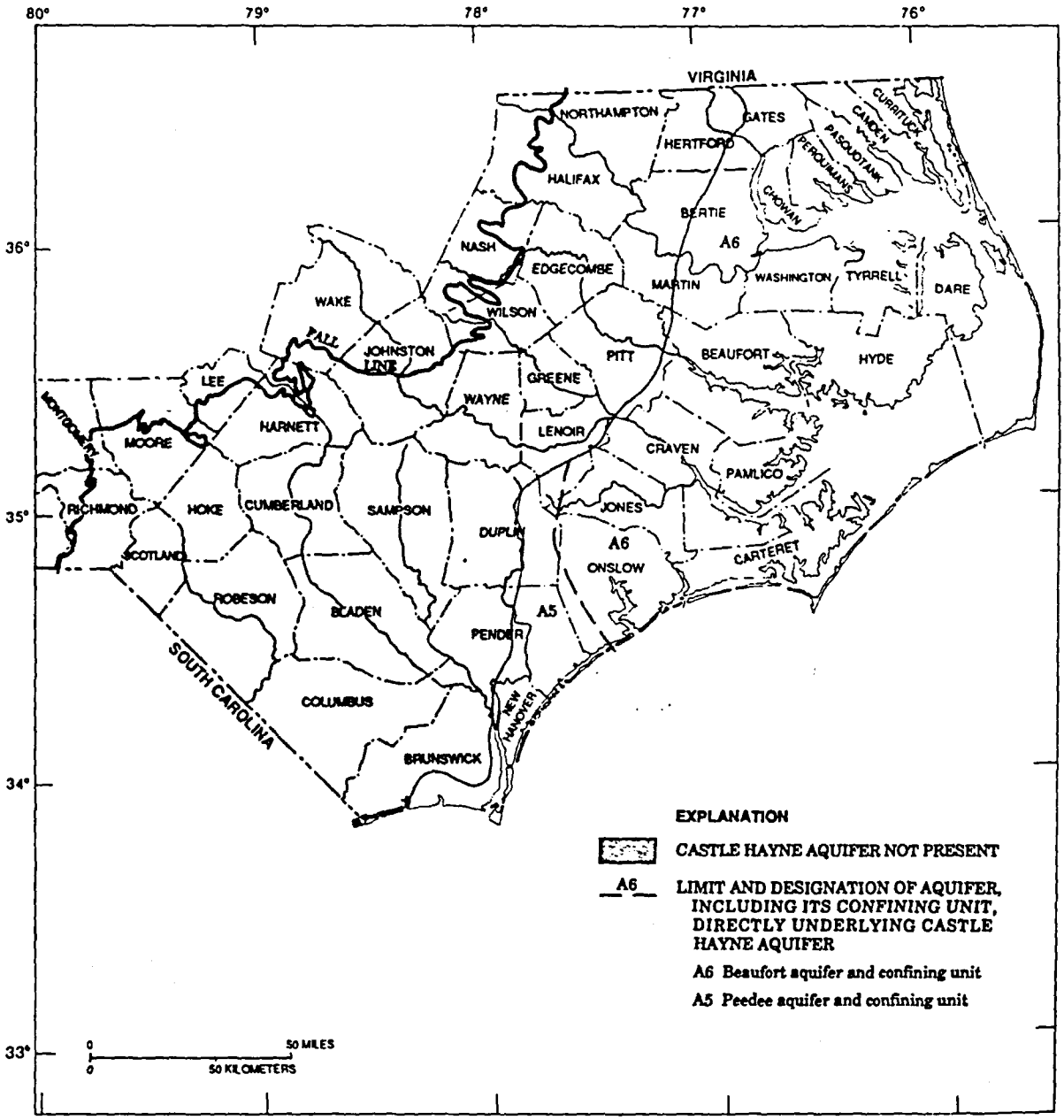


Figure 13.--Areal extent of the Castle Hayne aquifer (A7) and underlying aquifers (modified from Winner and Coble, 1989).

Beaufort Aquifer (A6) and Overlying Confining Unit (CU6)

The dark green and gray sands and clays that were identified as the Beaufort Formation of Paleocene age by Brown (1959) and later identified as rocks of Midway age by Brown and others (1972) comprise the bulk of the Beaufort aquifer (A6) the extent of which is shown in figure 14. As with the other hydrogeologic units, the definition of this aquifer was not restricted to a single geologic formation; the Beaufort aquifer may include parts of rock units that are older than the Beaufort Formation (Winner and Coble, 1989).

The Beaufort aquifer (A6) is composed of fine to medium glauconitic sands, clayey sands, and clay beds of marine origin. Shell and limestone beds are present but are less than 6 ft thick. The thickness of the Beaufort aquifer ranges from less than 10 ft along its western limit to more than 100 ft in the northern part of its eastern limit. In Camden and Currituck Counties, the aquifer thins toward the east or northeast. The average horizontal hydraulic conductivity of the aquifer was estimated to be about 36 ft/d, on the basis of lithologic and geophysical logs, with lower than average values in the northern and easternmost parts of the aquifer where the sand is finer and the aquifer contains more clay.

The Beaufort confining unit (CU6) consists of the uppermost sediments of the Beaufort Formation and possibly some younger clay, silt, and sandy clay. Over most of the area, the confining unit shows a gradation from sandy clay to clay, but contains distinct clay beds interlayered with fine sand or silt. The thickness of the confining unit ranges from zero to 80 ft and averages about 24 ft. The thicker parts of the confining unit are in and northeast of Washington County.

The Beaufort aquifer (A6) is covered entirely by younger rocks (fig. 14) and is not exposed at land surface. About 90 percent of the Beaufort aquifer (A6) and confining unit (CU6) are overlain by the Castle Hayne aquifer (A7). The remainder is overlain with the Yorktown aquifer (A4) from Pitt County northward near its updip limit (fig. 14). The upper Cape Fear, the Black Creek, and the Peedee aquifers and confining units underlie the Beaufort aquifer. The Peedee aquifer and confining unit (A5 and CU5) underlie about 80 percent of the area of the Beaufort aquifer (fig.

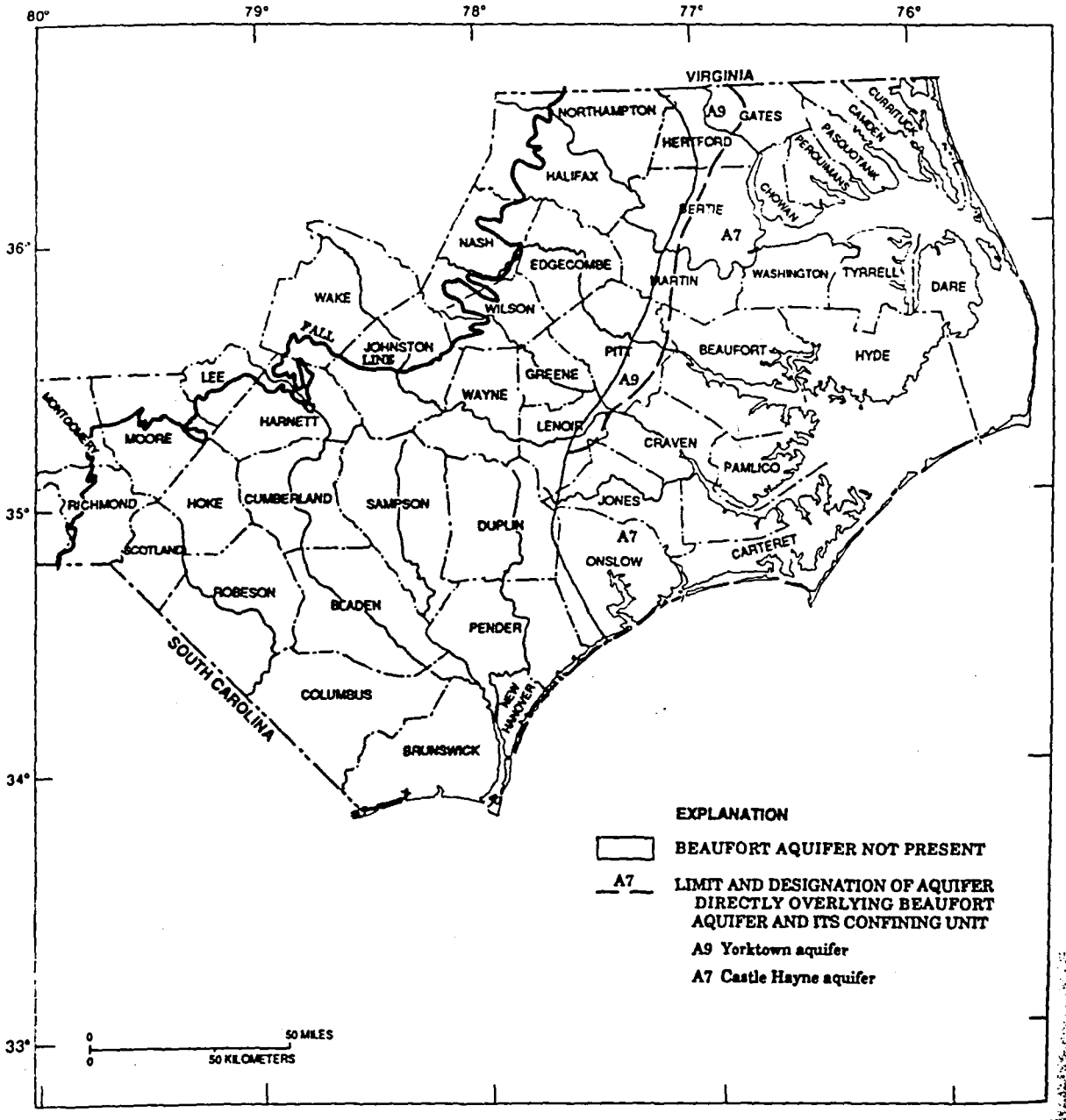


Figure 14.--Areal extent of the Beaufort aquifer (A6) and overlying aquifers (modified from Winner and Coble, 1989).

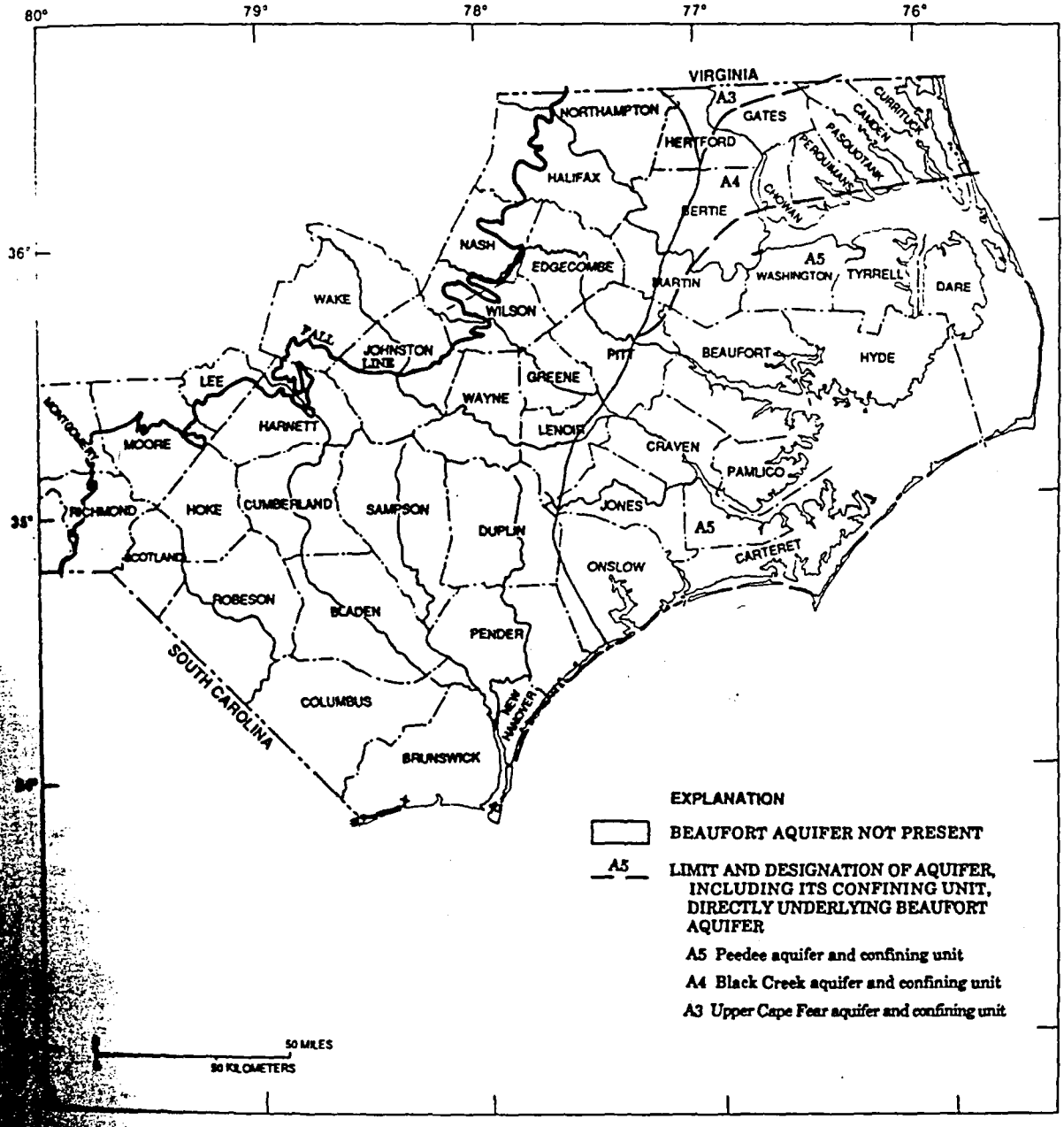


Figure 15.--Areal extent of the Beaufort aquifer (A6) and underlying aquifers (modified from Winner and Coble, 1989).

Peedee Aquifer (A5) and Overlying Confining Unit (CU5)

The Peedee aquifer (A5) is named for the Upper Cretaceous Peedee Sand of Clark and others (1912, p. 145) and the Peedee Formation of Stephenson and Rathbun (1923, p. 11), of which the aquifer is largely composed. The areal extent of the Peedee aquifer and overlying units is shown in figure 16.

The Peedee aquifer (A5) is composed of fine to medium-grained sands interbedded with clays and silts. Thin beds of consolidated calcareous sandstone and impure limestone are interlayered among the sands in some places, particularly in the southeastern Coastal Plain area. Shells are common throughout the unit. The top of the Peedee aquifer dips eastward at an average rate of about 24 ft/mi (feet per mile), but the dip is variable from about 10 ft/mi in the western part to over 32 ft/mi in the more deeply buried part along the coast. The aquifer thickness ranges from zero along its western limit to more than 300 ft along the coast from southern Onslow County to the South Carolina border. Northeast of Onslow County, the maximum thickness of the aquifer is less than 200 ft and the unit contains saltwater. The average horizontal hydraulic conductivity of the Peedee aquifer was estimated from geophysical logs to be about 33 ft/d by Winner and Coble (1989).

The Peedee confining unit (CU5) is composed of clay, silty clay, and sandy clay. Winner and Coble (1989) did not identify the confining unit with a particular geologic unit, but the unit is composed primarily of sediments at the Cenozoic-Mesozoic boundary. The average thickness of the Peedee confining unit is about 25 ft. In the eastern part of the confining unit, thickness may reach 60 ft but commonly does not exceed 30 to 35 ft.

Black Creek Aquifer (A4) and Overlying Confining Unit (CU4)

The Black Creek aquifer (A4) (Winner and Coble, 1989) includes Upper Cretaceous sediments of both the Black Creek and underlying Middendorf Formations (fig. 17). The Black Creek Formation consists mainly of thinly-laminated gray to black clay, interbedded with gray to tan sands. Outcrops also exhibit sand or clay-dominated lenses. The Middendorf Formation

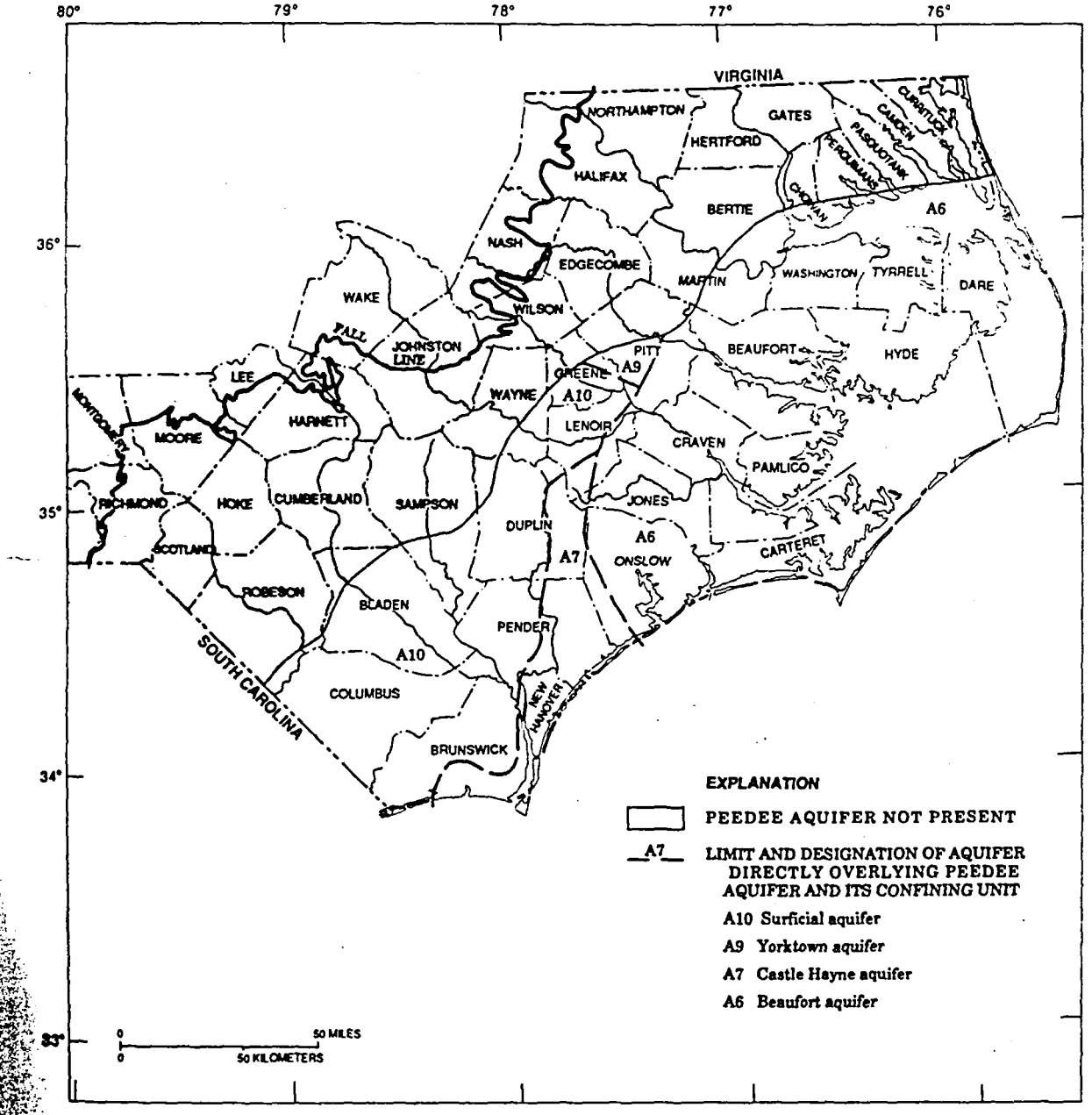


Figure 16.--Areal extent of the Peedee aquifer (A5) and overlying aquifers (modified from Winner and Coble, 1989).

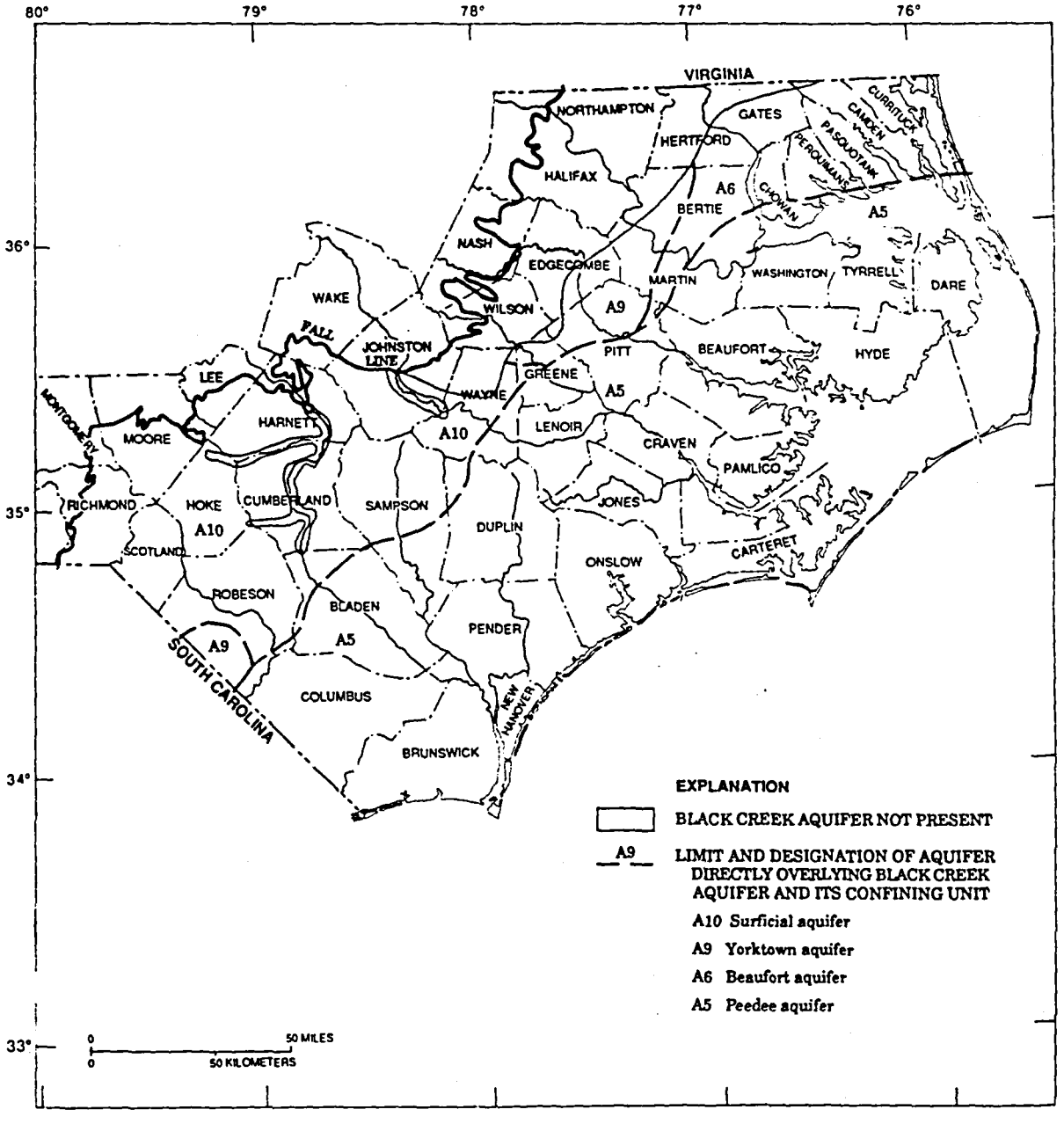


Figure 17.--Areal extent of the Black Creek aquifer (A4) and overlying aquifers (modified from Winner and Coble, 1989).

consists mainly of a fine to medium sand, interbedded with silty clay, coarser channel sand, and thinly laminated sand and clay. The horizontal hydraulic conductivity of the Black Creek aquifer as estimated by Winner and Coble (1989) ranges from about 15 to 50 ft/d, based on geophysical logs and aquifer tests.

The Black Creek aquifer and confining unit (A4 and CU4) are overlain by the Peedee (A5 and CU5), Beaufort (A6 and CU6), and Yorktown (A9 and CU9), aquifers and confining units and by the surficial aquifer (A10) (fig. 17). The Peedee aquifer overlies the eastern two-thirds of the Black Creek aquifer and confining unit, and the surficial aquifer overlies the Black Creek from the Fall Line to the updip limit of the Peedee in the southern Coastal Plain, except for a small area in Robeson County where it is overlain by the Yorktown aquifer. The Yorktown and Beaufort aquifers overlie the Black Creek aquifer and confining unit along its western limit in the northern Coastal Plain.

The Black Creek confining unit (CU4) is primarily composed of the uppermost beds of the Black Creek Formation and consists of clay, silty clay, and sandy clay. In the northern part of the Coastal Plain, it may also include clay of the lower parts of the Beaufort or Yorktown Formations. In the deeper subsurface, clay in the lower part of the Peedee Formation may also be included as a part of this confining unit. In the Sand Hills area (see inset, fig. 1), where the Black Creek aquifer (A4) is composed of the Middendorf Formation, confining unit CU4 is composed of the uppermost clay of the Middendorf Formation. In the highly dissected Sand Hills, the Middendorf clay is cut through in many places by streams; thus the Black Creek confining unit does not exist at these locations. Farther east, the channels of larger streams, such as the Cape Fear and Neuse Rivers, also have cut through the confining unit to allow direct hydraulic connection between the streams and the Black Creek aquifer. The thickness of the confining unit averages about 45 ft but it may be more than 168 ft thick in places in the eastern part of the Coastal Plain.

Upper Cape Fear Aquifer (A3) and Overlying Confining Unit (CU3)

Winner and Coble (1989) recognized that the Upper Cretaceous Cape Fear Formation could be separated into two distinct hydrogeologic units, largely

on the basis of effective confining beds between the upper and lower parts in Brunswick and adjacent counties near the South Carolina border. The sediments of the upper Cape Fear aquifer (A3), (fig. 18) are alternating beds of sand and clay. The individual beds are commonly 3 to 5 ft thick, but range up to 15 ft thick.

The upper Cape Fear aquifer (A3) varies in thickness from about 10 ft along its western edge to nearly 500 ft in central Tyrrell County. The average thickness of the aquifer is slightly more than 100 ft. The aquifer is thickest beneath the Albemarle-Pamlico Peninsula east of Beaufort and Washington Counties. The horizontal hydraulic conductivity of the aquifer was estimated from geophysical logs to average about 30 ft/d, with values ranging from 20 to 70 ft/d (Winner and Coble 1989).

As described by Winner and Coble (1989), the upper Cape Fear confining unit (CU3) consists of nearly continuous clay, silty clay, and sandy clay beds belonging either to the Middendorf Formation in the Sand Hills area or to the Black Creek Formation. The thickness of the confining unit averages about 48 ft (Winner and Coble, 1989), but may exceed 100 ft in places near the South Carolina border, near the southeastern corner of Duplin County and in Dare County. Along the western limit of the upper Cape Fear aquifer (A3), the Cape Fear and Neuse Rivers have cut through the confining unit; the same is true along the Tar and Roanoke Rivers.

The upper Cape Fear aquifer and confining unit (A3 and CU3) are overlain by the Black Creek aquifer (A4) in about 90 percent of its area (fig. 18). The Yorktown aquifer (A9) overlies the upper Cape Fear in the northwest, and the Beaufort aquifer (A6) overlies it in parts of Gates and Hertford Counties. The lower Cape Fear aquifer and confining unit (A2 and CU2) underlie the upper Cape Fear aquifer (A3) in about three-fourths of its area (fig. 19). Elsewhere, the upper Cape Fear is in contact with basement rocks.

Lower Cape Fear Aquifer (A2) and Overlying Confining Unit (CU2)

The lower Cape Fear aquifer (A2) in figure 20 consists mostly of older sand beds of the Cape Fear Formation similar to those beds described for the

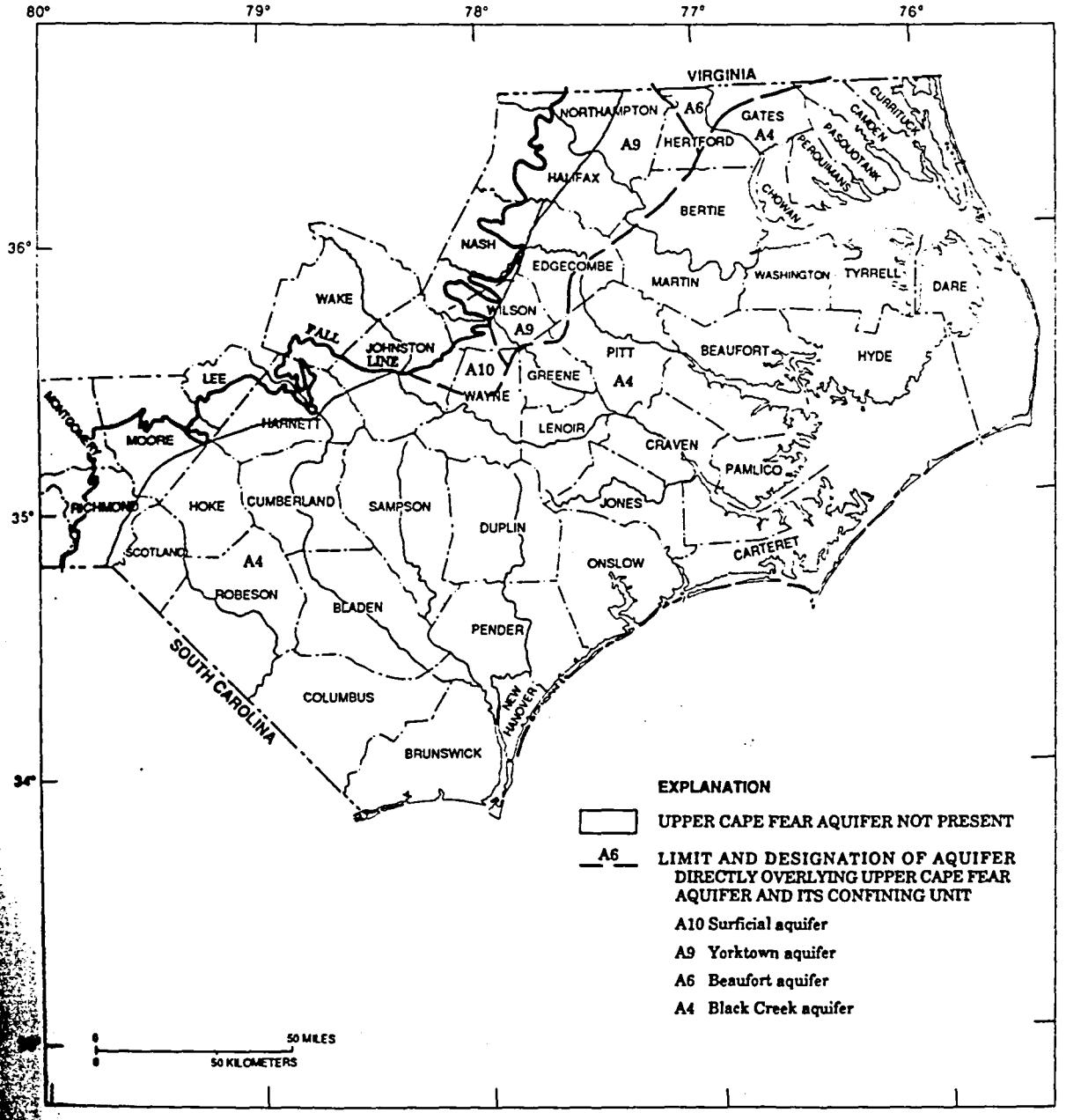


Figure 18.--Areal extent of the upper Cape Fear aquifer (A3) and overlying aquifers (modified from Winner and Coble, 1989).

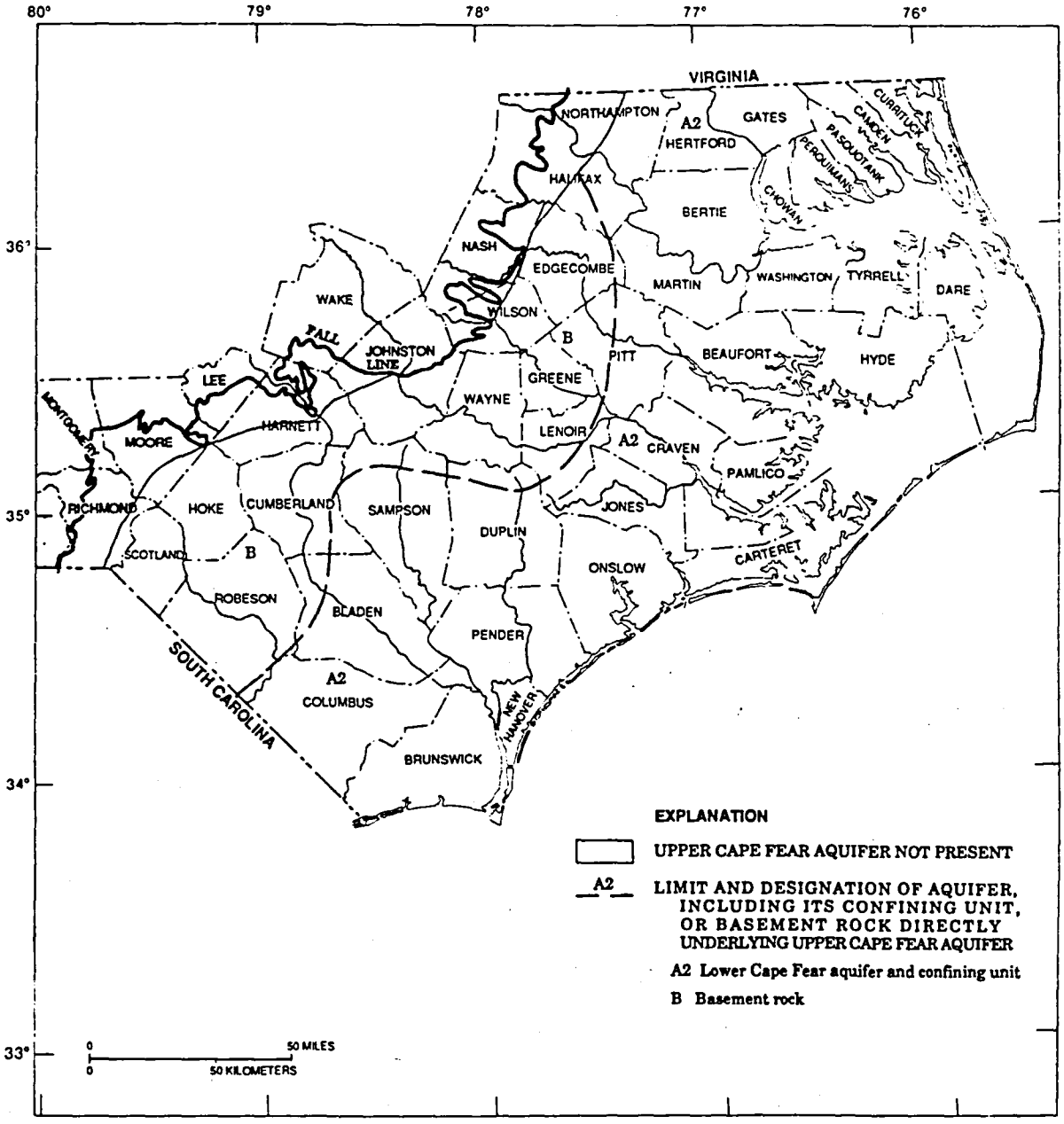


Figure 19.--Areal extent of the upper Cape Fear aquifer (A3) and underlying aquifers or basement rock (modified from Winner and Coble, 1989).

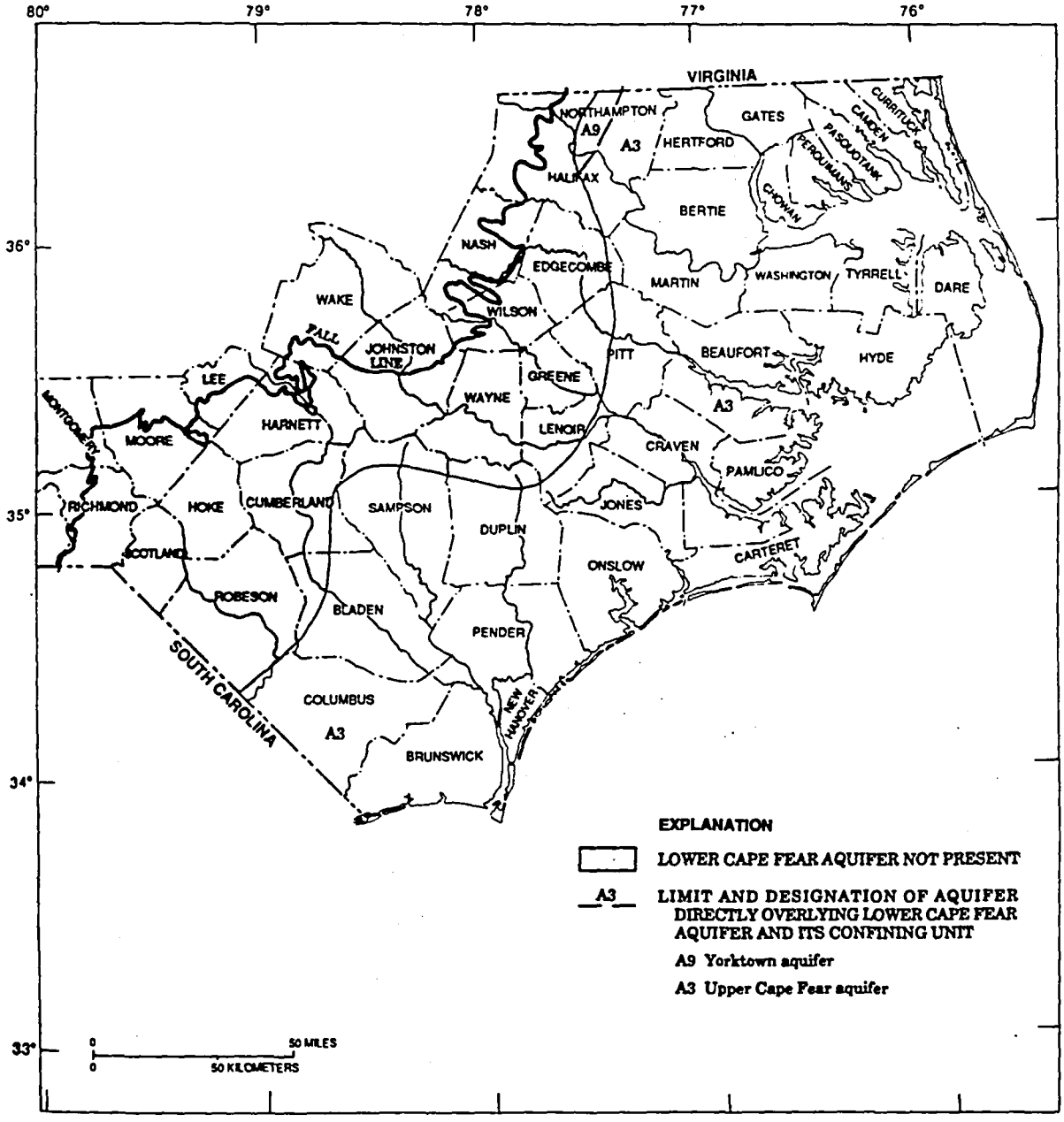


Figure 20.--Areal extent of the lower Cape Fear aquifer (A2) and overlying aquifers (modified from Winner and Coble, 1989).

upper Cape Fear aquifer (A3). In the southern Coastal Plain, Winner and Coble (1989) viewed these sediments largely as a regressive phase of the Cape Fear Formation having a separate hydrologic identity from overlying and younger Cape Fear sand units.

The lower Cape Fear aquifer (A2) strikes northeast and dips southwest at a rate of 15 to 35 ft/mi. Its thickness ranges from a few feet along its western margin to more than 400 ft in the northeastern Coastal Plain. The average hydraulic conductivity of the aquifer was estimated by Winner and Coble (1989) from geophysical logs to be about 34 ft/d. Individual values ranged from 20 to 75 ft/d.

The lower Cape Fear confining unit (CU2) is composed of clay and sandy-clay beds that belong largely to the Cape Fear Formation. The average thickness of the confining unit is about 50 ft. The confining unit exceeds 75 ft in thickness throughout the eastern quarter of the Coastal Plain and in parts of Bertie and Halifax Counties and is more than 100 ft thick in parts or all of Pasquotank, Camden, Currituck, Columbus, and Brunswick Counties.

The lower Cape Fear aquifer and confining unit (A2 and CU2) are overlain by the upper Cape Fear aquifer (A3) everywhere except for a small area near the Fall Line in Northampton County where the Yorktown aquifer (A9) overlies them (fig. 20). The Lower Cretaceous aquifer and confining unit (A1 and CU1) underlie the lower Cape Fear aquifer in the eastern half of the Coastal Plain (fig. 21). Elsewhere, the lower Cape Fear aquifer lies on basement rocks.

Lower Cretaceous Aquifer (A1) and Overlying Confining Unit (CU1)

Sediments below the Cape Fear Formation are regarded by most investigators as belonging to the Lower Cretaceous Series and, possibly, to older rocks (Winner and Coble, 1989). Thus, the name Lower Cretaceous aquifer (A1) was chosen to designate this hydrogeologic unit which is the lowermost aquifer defined in this study. The extent of aquifer A1 is shown in figure 21. Various investigators have established that the updip beds of the Lower Cretaceous aquifer are largely nonmarine in origin, but the

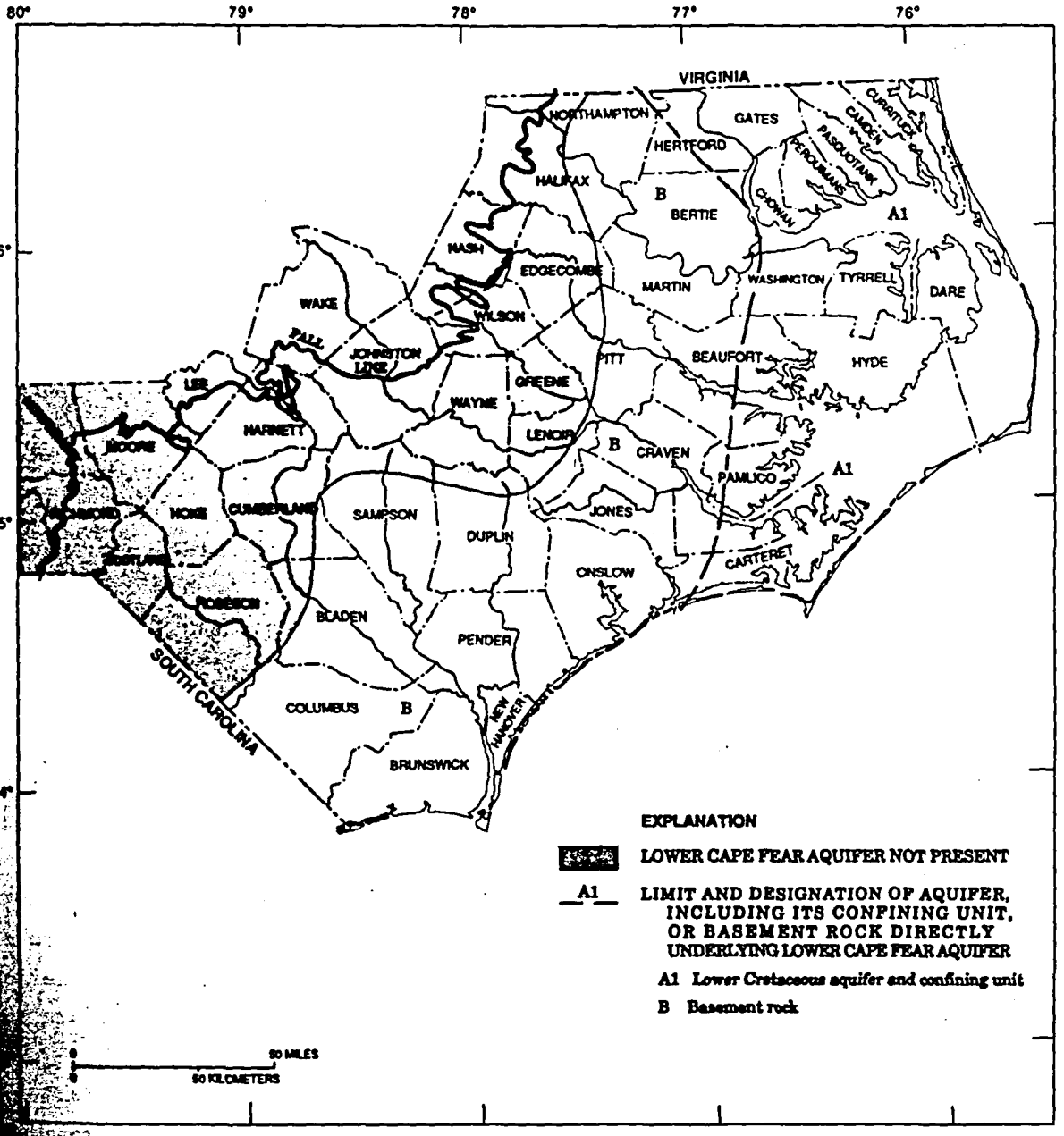


Figure 21.--Areal extent of the lower Cape Fear aquifer (A2) and underlying aquifers or basement rock (modified from Winner and Coble, 1989).

incidence of beds of marine origin increases downdip towards the coast. The nonmarine beds are represented by shales, sands, and sands and gravel. Marine beds are chiefly limestones that may be sandy or dolomitic. Data on horizontal hydraulic conductivity of the Lower Cretaceous aquifer are lacking in North Carolina, but Winner and Coble (1989) inferred from work by Brown and Cosner (1974) in Virginia that the hydraulic conductivity of this unit nearby in Virginia ranged from 10 to 40 ft/d, and in North Carolina may range from 20 to 30 ft/d.

The thickness of the Lower Cretaceous aquifer (A1) ranges from about 15 ft near its western limit to more than 2,000 ft in Currituck County. The average thickness of the Lower Cretaceous aquifer is about 500 ft.

The Lower Cretaceous confining unit (CU1) consists of clay and sandy-clay beds that belong to either sediments of Early Cretaceous or Late Cretaceous age. The thickness of the unit averages about 46 ft but is nearly 70 ft in Camden and Currituck Counties. The Lower Cretaceous aquifer and confining unit are overlain everywhere by the lower Cape Fear aquifer (A2) and underlain everywhere by crystalline basement rocks (Winner and Coble, 1989).

SIMULATION OF GROUND-WATER FLOW

Equation of Ground-Water Flow

The basic ground-water flow equation used in this report is of the form:

$$\frac{\partial}{\partial x}\left[T_{xx}\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[T_{yy}\frac{\partial h}{\partial y}\right] + \frac{b\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right] = S\frac{\partial h}{\partial t} + bW(x,y,z,t) \qquad (1)$$

in which, using units of time (T) and length (L):

T_{xx} = principal component of the transmissivity tensor in the x direction (L^2T^{-1});

T_{yy} = principal component of the transmissivity tensor in the y direction (L^2T^{-1});

K_{zz} = principal component of the hydraulic conductivity tensor in the z direction (LT^{-1});

h = hydraulic head (L);

S = storage coefficient (dimensionless);

b = thickness of hydraulic unit (L);

t = time (T);

x,y,z = space coordinates (L);

W(x,y,z,t) = volumetric flux per unit volume (T^{-1}); (Trescott, 1975).

The derivation of this equation will not be explained here, but discussions of its development may be found in Trescott (1975) and Trescott and Larson (1976).

Digital Model of Ground-Water Flow

The digital model used in this study to solve a finite-difference form of the preceding ground-water flow equation (eq. 1) is described by Leahy (1982). Leahy's model is a modified version of a three-dimensional finite-difference flow model program described by Trescott (1975) and Trescott and Larson (1976). The model assumes that all flow in the aquifers is horizontal and all flow in the confining units is vertical. Leahy's modification reduces computer-memory requirements and better simulates confining-unit and aquifer pinchouts.

Grid Design

The model area is divided into a rectangular grid having 11 layers, 60 rows, and 48 columns. The grid spacing is variable. The smallest rectangle is 12.25 mi^2 and the largest is 56.25 mi^2 (fig. 22). This grid is designed to be compatible with the regional model grid described by Leahy and Martin (in press) intended for simulating the entire North Atlantic Coastal Plain aquifer system in that each rectangle of the regional grid is divided into four small, local (North Carolina) grids (12.25 mi^2).

Each layer of the North Carolina model has 2,880 rectangular blocks, which total 31,680 blocks for the 11 layers. The model nodes are located at the center of each block. Each input value assigned to a node is considered to be an average value for the entire block. Likewise, output values (hydraulic head and drawdown) are also average values for that block. An

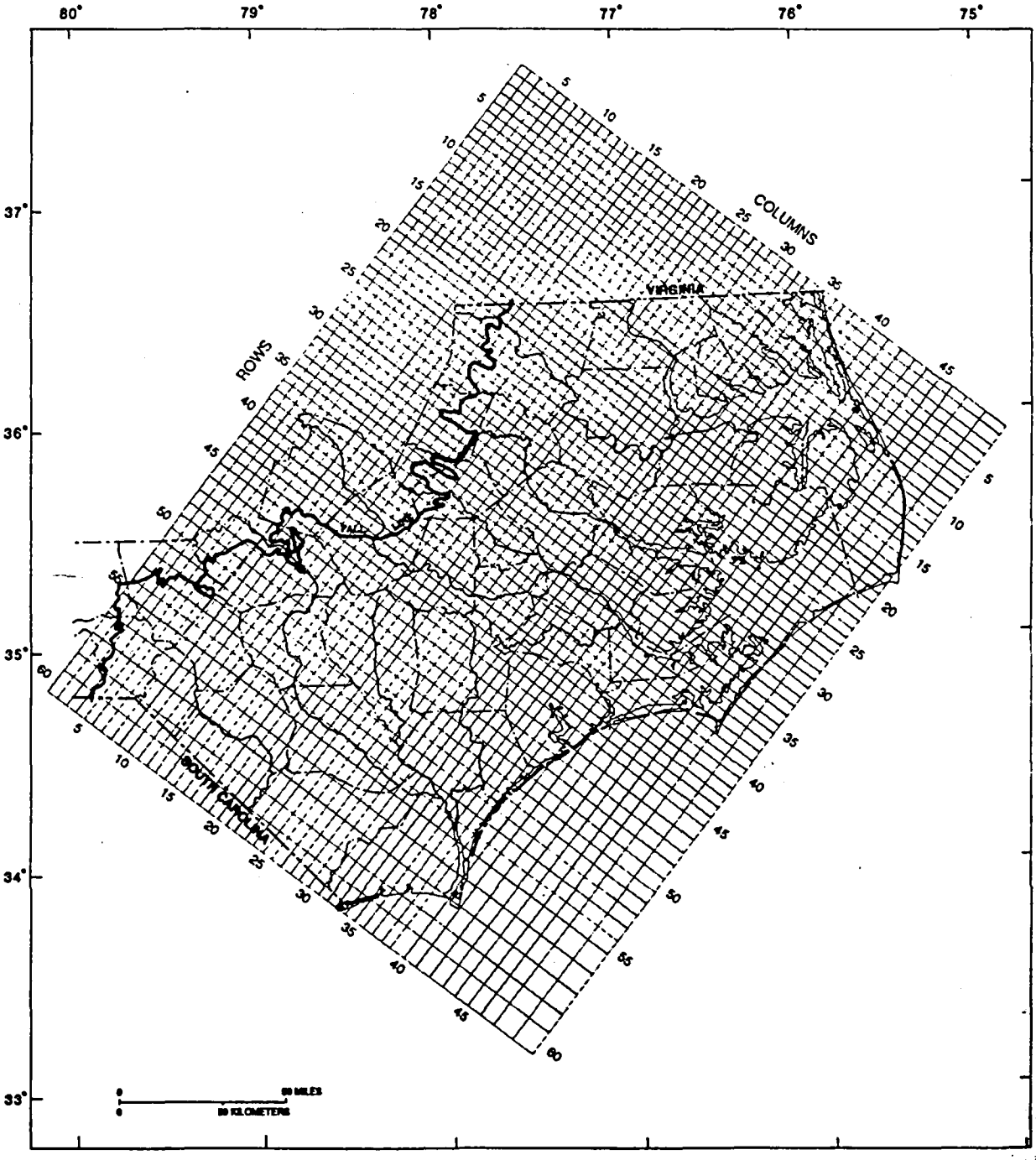


Figure 22.--Finite-difference grid for the North Carolina Coastal Plain aquifer system flow model.

assumption inherent in this approach is that the Cartesian coordinate axes x and y are aligned with the principal components of the transmissivity tensor T_{xx} and T_{yy}.

Model Boundaries

The confined aquifers (A9-A1) thin to extinction at their westernmost limit (near the Fall Line). Therefore, the westernmost limit of each aquifer is treated as a no-flow boundary. The westernmost limit of the surficial aquifer (A10) coincides with the westernmost limit of the North Carolina Coastal Plain study area and is also treated as a no-flow boundary.

The eastern limit of of fresh ground-water flow system is assumed to be at an equal concentration line where the water contains 10,000 mg/L of chloride, and the line is also treated as a no-flow boundary. Where this concentration line occurs in each aquifer within the model area is referred to as the freshwater-saltwater boundary. It is important to note that this assumption is considered valid only in areas where there are negligible drawdowns due to pumping at or near the freshwater-saltwater boundaries. Where a layer's freshwater-saltwater boundary occurs outside the model area, the eastern model boundary for that layer is a specified-flux boundary with fluxes being supplied by the regional model. In this report, the eastern limits of the aquifers are shown only if they occur over land, although the aquifers were actually modeled to their freshwater-saltwater boundaries or to the boundary of the model. The upper boundary of each confined aquifer is the bottom of its associated confining unit and is treated in the model algorithm as if it were a head-dependent flux boundary.

The bottom boundary of each aquifer is either a head-dependent flux boundary (where another aquifer and confining unit are present below) or a no-flow boundary (where bedrock or a freshwater-saltwater boundary underlie the aquifer). Where the modeled area of an aquifer is bounded by the Virginia or South Carolina State borders, these borders are treated as specified-flux boundaries to simulate the movement of water across the State lines. Again, the fluxes are supplied from the regional model and simulate not only natural flow, but also induced flow due to the effects of pumping inside and outside the North Carolina study area. The uppermost active

model node at any location represents a stream or lake surface elevation and is treated as a constant head node; the lowermost active node at any given location represents a freshwater-saltwater boundary or bedrock and is treated as a no-flow boundary.

Model Input

The following sections discuss how aspects of the conceptual model of the aquifer system were represented numerically in the flow model input requirements. The model input requirements are shown schematically in figure 23. Printouts of model input for the calibrated model are available from the U.S. Geological Survey, WRD, Raleigh, North Carolina. Many of the items discussed under "Model Input" also relate to the water budget aspect of the conceptual model of the aquifer system (fig. 3).

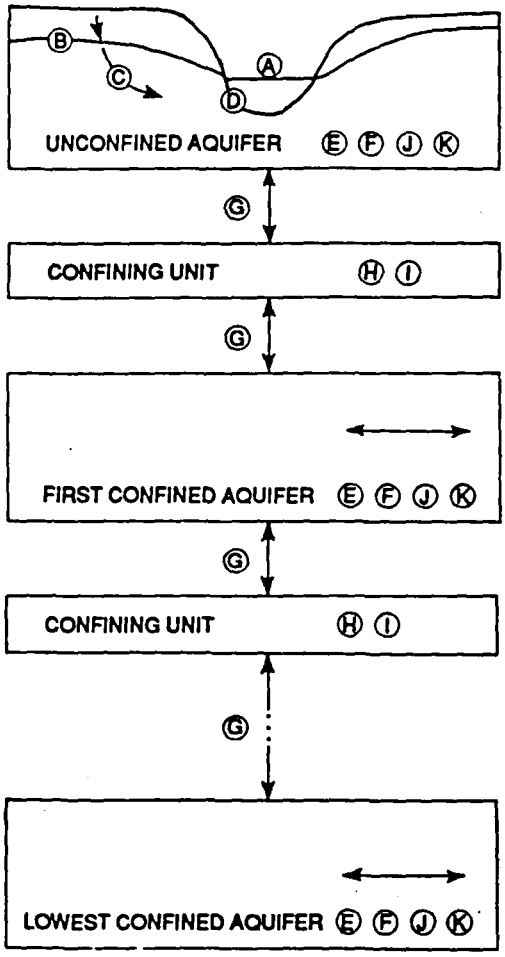
Ground-water recharge

On a nodal basis, recharge to the surficial aquifer (A10) was estimated to range between 12 and 20 in/yr over the North Carolina Coastal Plain and to average nearly 14 in. Each water-table node was given a recharge value of 12, 14, 16, or 20 in/yr, based on (1) soil characteristics from U.S. Soil Conservation Service maps (Tant and others, 1974), (2) estimates of recharge to thick sandy soils by Heath (1980), and (3) estimates of base flow to the North Carolina Coastal Plain streams from hydrograph separation using techniques developed by Rorabaugh (1964) and Daniel (1976), as described by Wilder and Simmons (1982). Maximum recharge rates (fig. 24) occur in the Sand Hills area and minimum rates occur generally in the east, where surficial soils have a high clay content.

Streambed leakance

The exchange of water between the surficial aquifer and a stream through the streambed can be expressed for steady-state conditions and on a unit area basis by the following equation, which is an expression of Darcy's Law:

$$BF = SL\ (h_a - h_s) \qquad (2)$$



EXPLANATION

Ⓐ MODEL INPUT REQUIREMENTS

- A Stream-surface or lake-surface altitude
- B Water-table altitude
- C Recharge to water table (QRE)
- D Stream channel leakance (TK)
- E Transmissivity of aquifer (T)
- F Specific yield or storage coefficient of aquifer (S)
- G Deep percolation (DP)
- H Effective thickness of confining unit (b)
- I Vertical hydraulic conductivity of confining unit (Kv)
- J Water-level data required for calibration
- K Ground-water pumpage

⟶ FLOW DIRECTION

Figure 23.--Schematic representation of model input requirements.

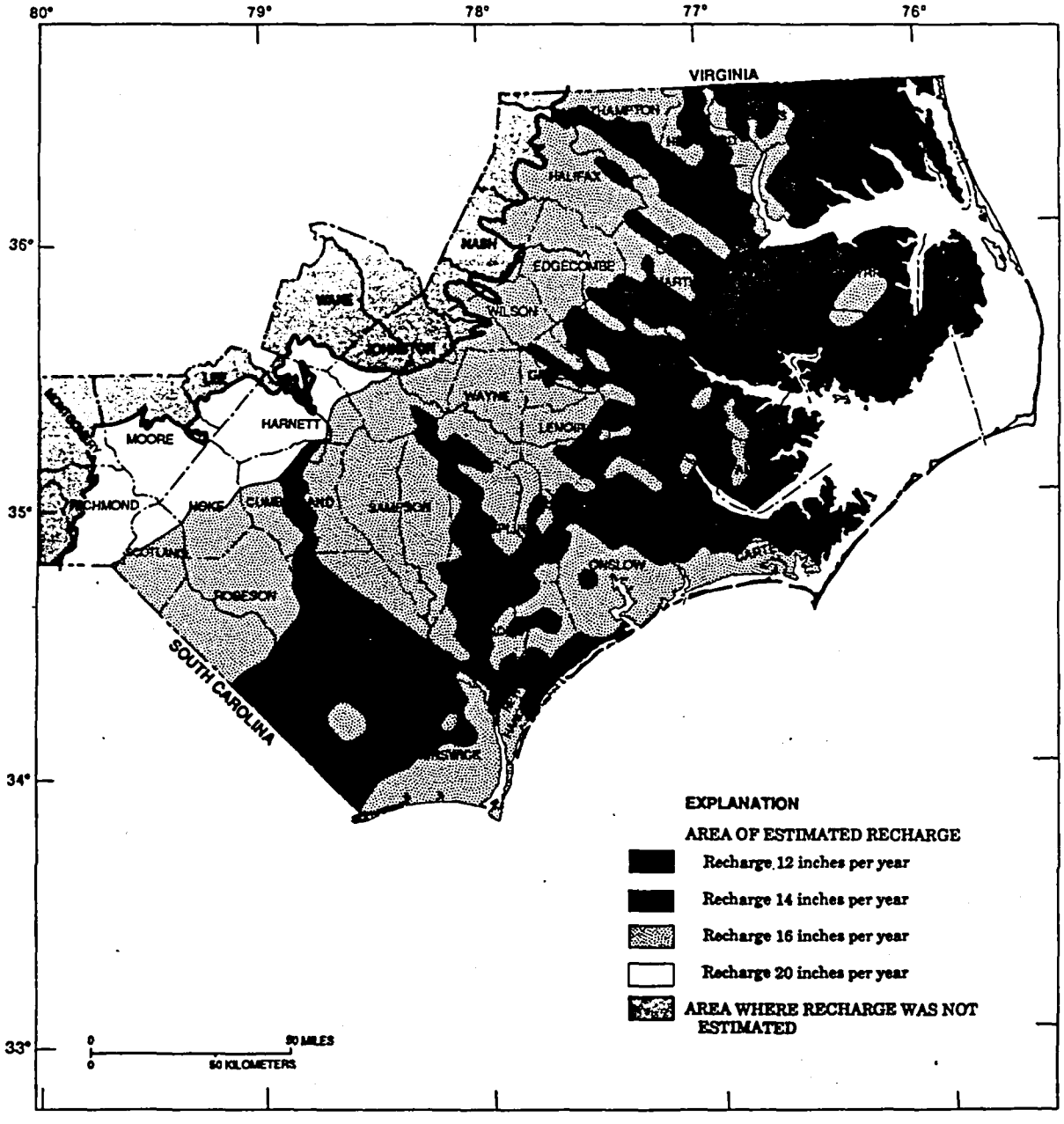


Figure 24.--Estimated recharge to surficial aquifer (A10) from precipitation (modified from Winner and Coble, 1989).

where:

BF = stream base flow (ground-water contribution to streamflow), in cubic feet per day per square foot;

SL = streambed leakance factor, computed as the ratio of the vertical hydraulic conductivity (K_v) of the streambed material, in cubic feet of water per day per square foot $(ft^3/d)/ft^2$, or ft/d, to the thickness of the streambed material (b), in feet, yielding units of (ft/d)/ft, or per day;

h_a = estimated altitude of water table in the surficial aquifer, in feet;

h_s = estimated altitude of stream surface, in feet.

The average water-table altitude and lowest stream altitude within each appropriate block were estimated from 1:24,000 and 1:62,250 scale U.S. Geological Survey topographic maps. The lowest stream altitude for each block was chosen because it was considered the "controlling" elevation governing flow from the surficial aquifer (A10) to the stream system. Base flow was determined from the following equation, which is for steady-state conditions:

$$BF = QRE \pm DP \qquad (3)$$

where:

BF = stream base flow, in cubic feet per square foot per day;

QRE = ground-water recharge to the surficial aquifer, in feet per second;

DP = deep percolation into or flow out of the underlying confined aquifer system, in feet per day.

Ground-water recharge (QRE) was determined for and input into each block as described earlier in the "Ground-Water Recharge" section of this report. Deep percolation (DP) was calculated for each block from simulations for predevelopment steady-state conditions in which the water table was treated as a constant-head boundary. Average base flow for each

block could then be calculated from equation (3) above, and the resulting base-flow value substituted into equation (2) to solve for streambed leakance (SL). A constant-head value equal to the stream altitude value was then assigned to each node overlying the water table. This procedure allowed fairly realistic simulation of water-table behavior during transient simulations. For example, as the water table is drawn down due to pumping from a confined aquifer below, base flow to streams is reduced; if the water table is drawn down below stream level, induced infiltration takes place, and the stream "recharges" the surficial aquifer.

The mechanics of simulations involving streams and streambed leakance are discussed in more detail in the "Model Calibration" section of this report; the important points here are the mechanics of calculating streambed leakance and the recognition that the streambed leakances are not reflective of leakances of real streambeds, but represent an "effective" streambed for an entire block. Thus, "model" streambed leakances (fig. 25) are much less than "real" streambed leakances. The distribution of streambed leakance values used as model input are shown in figure 25.

Transmissivity of aquifers

Transmissivity (T) is equal to $K_h b$, where K_h is the horizontal hydraulic conductivity of the aquifer and b is the thickness of the aquifer. The model employs the units of feet squared per second for transmissivity, but it is reported in units of feet squared per day (ft^2/d) in the text.

Initial estimates of transmissivity for model input were determined primarily from examination of geophysical logs. The character of the permeable material within each aquifer was interpreted from the logs, and a horizontal hydraulic conductivity (K_h) value of the aquifer material was assigned to the unit, roughly according to guidelines given in Morris and Johnson (1967, table 5). Average values of K_h determined in this manner ranged from 22 ft/d in the Yorktown aquifer (A9) to 65 ft/d in the Castle Hayne aquifer (A7) (Winner and Coble, 1989.). The hydraulic conductivity was then multiplied by the thickness of permeable material within each aquifer to arrive at a transmissivity value. Clay and silt layers were not included as part of aquifer thickness in computing T. The character of the

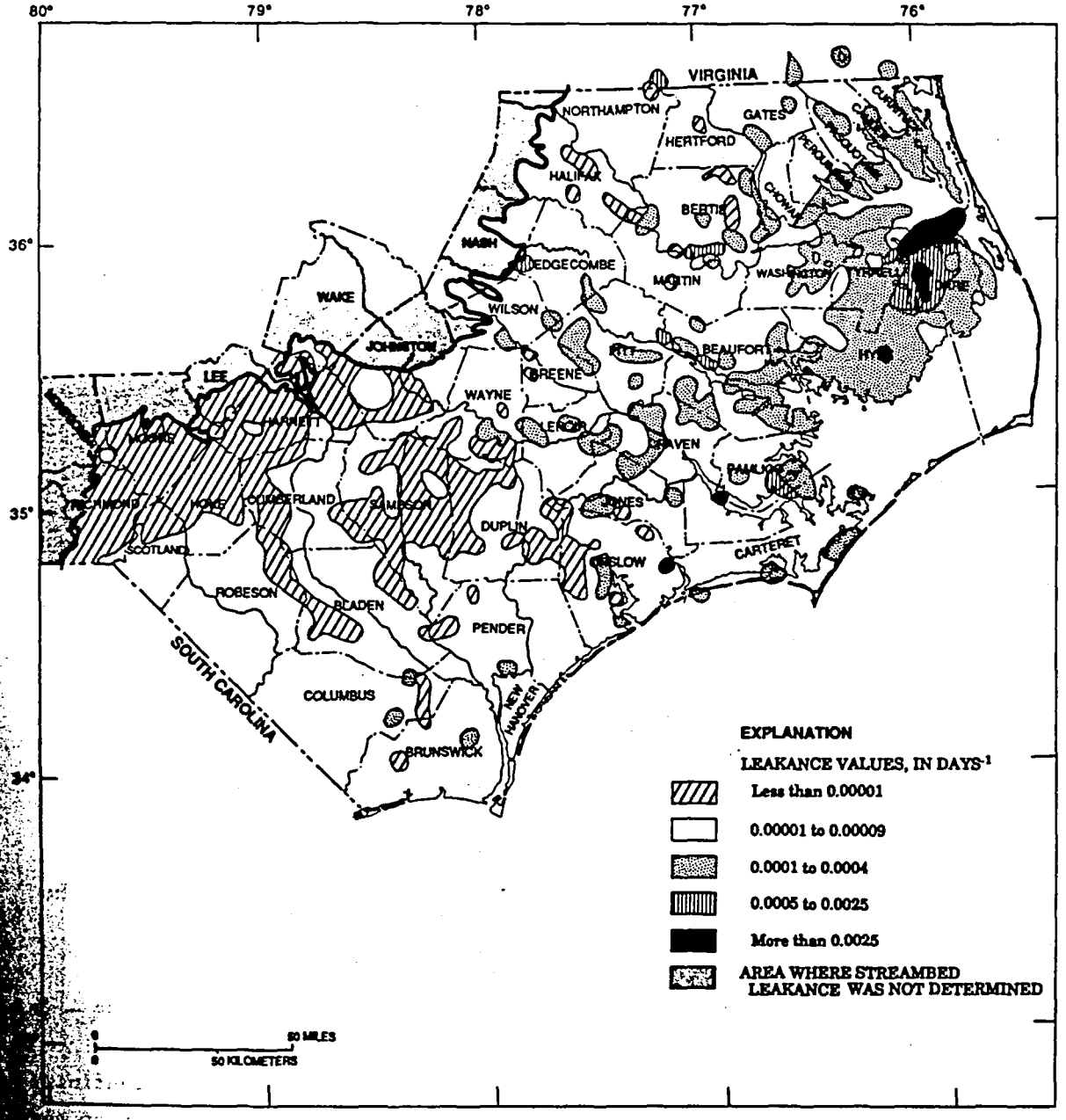


Figure 25.--Distribution of estimated streambed leakance.

permeable material was verified from geologists' logs where available. Where available and appropriate, existing aquifer-test data were used to confirm the transmissivity values.

Maps showing transmissivity used in model simulation after calibration for aquifers A9 through A1 are shown in figures 26 through 34. Transmissivities diminish to zero at the western limits of all units except the surficial aquifer (A10). Maximum transmissivities of slightly more than 200,000 ft^2/d occur in the Castle Hayne aquifer (A7) (fig. 28). Maximum T values in other aquifers seldom exceeded 10,000 ft^2/d. The rationale for varying transmissivity during the calibration process is discussed under "Model Calibration."

Storage coefficient of aquifers

In this study, a storage coefficient value of 1×10^{-4} was assigned to all active nodes in confined aquifers; for unconfined conditions, values ranging from 1×10^{-1} to 1.5×10^{-1} were used. Results from aquifer tests in the North Carolina Coastal Plain indicate that 1×10^{-4} is of the correct order of magnitude for a storage coefficient value for a confined aquifer.

Leakance of confining units

In the model used for this study, confining units were not represented as separate layers. Rather, the effects of vertical flow through confining units were incorporated in the vertical components of flow in the adjacent aquifers by use of a leakance term (TK) defined as the ratio of K_v/b for each confining unit, where K_v is the vertical hydraulic conductivity of the confining unit and b is its effective thickness.

The effective thickness of confining units was often less than the total thickness because most confining units contain thin layers of permeable material. The thickness of permeable layers within each confining unit was subtracted from the total confining-unit thickness to arrive at an effective thickness. Winner and Coble (1989) give effective thickness for each confining unit identified in the North Carolina Coastal Plain.

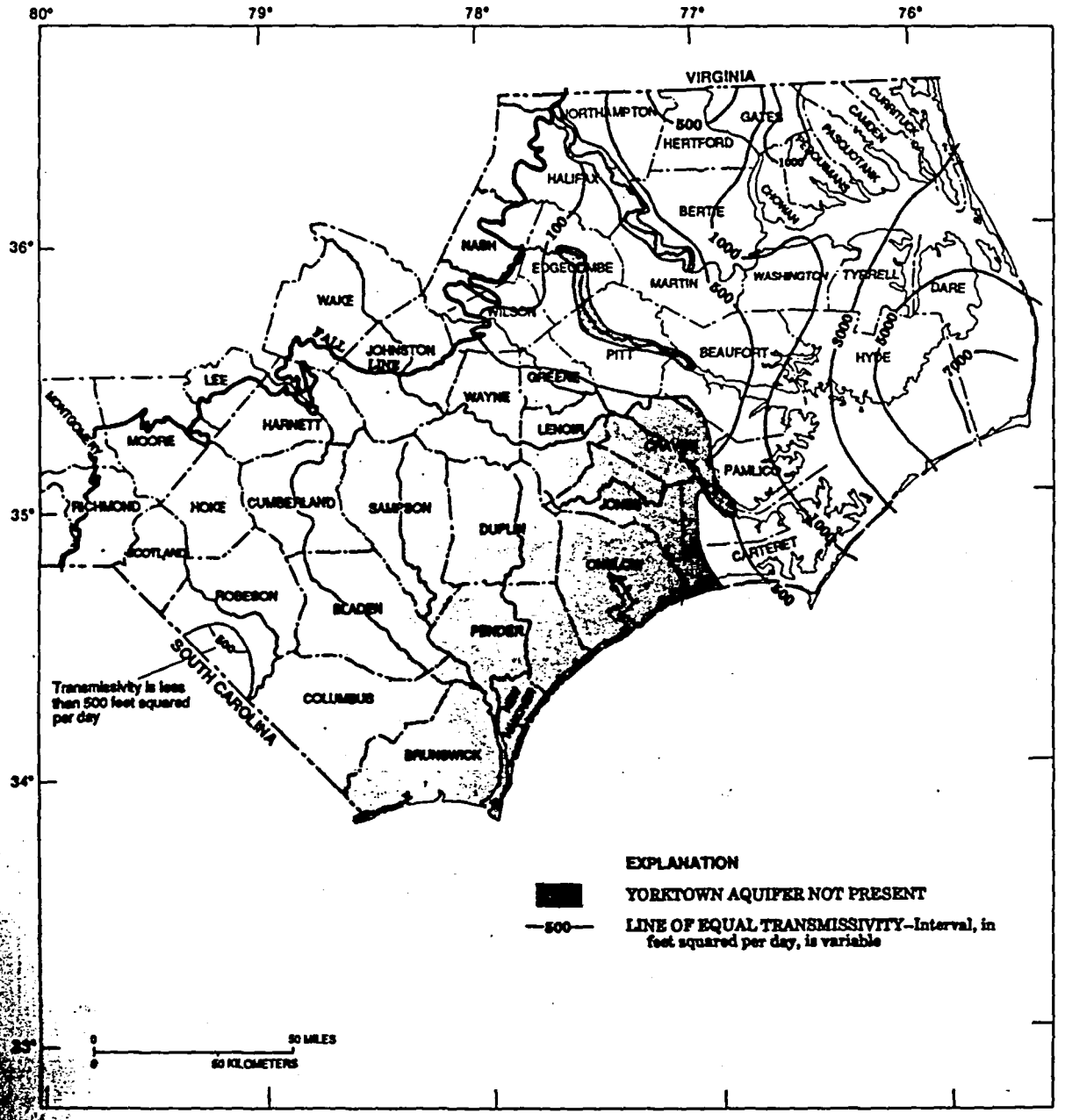


Figure 26.--Transmissivity of the Yorktown aquifer (A9) used in model simulations.

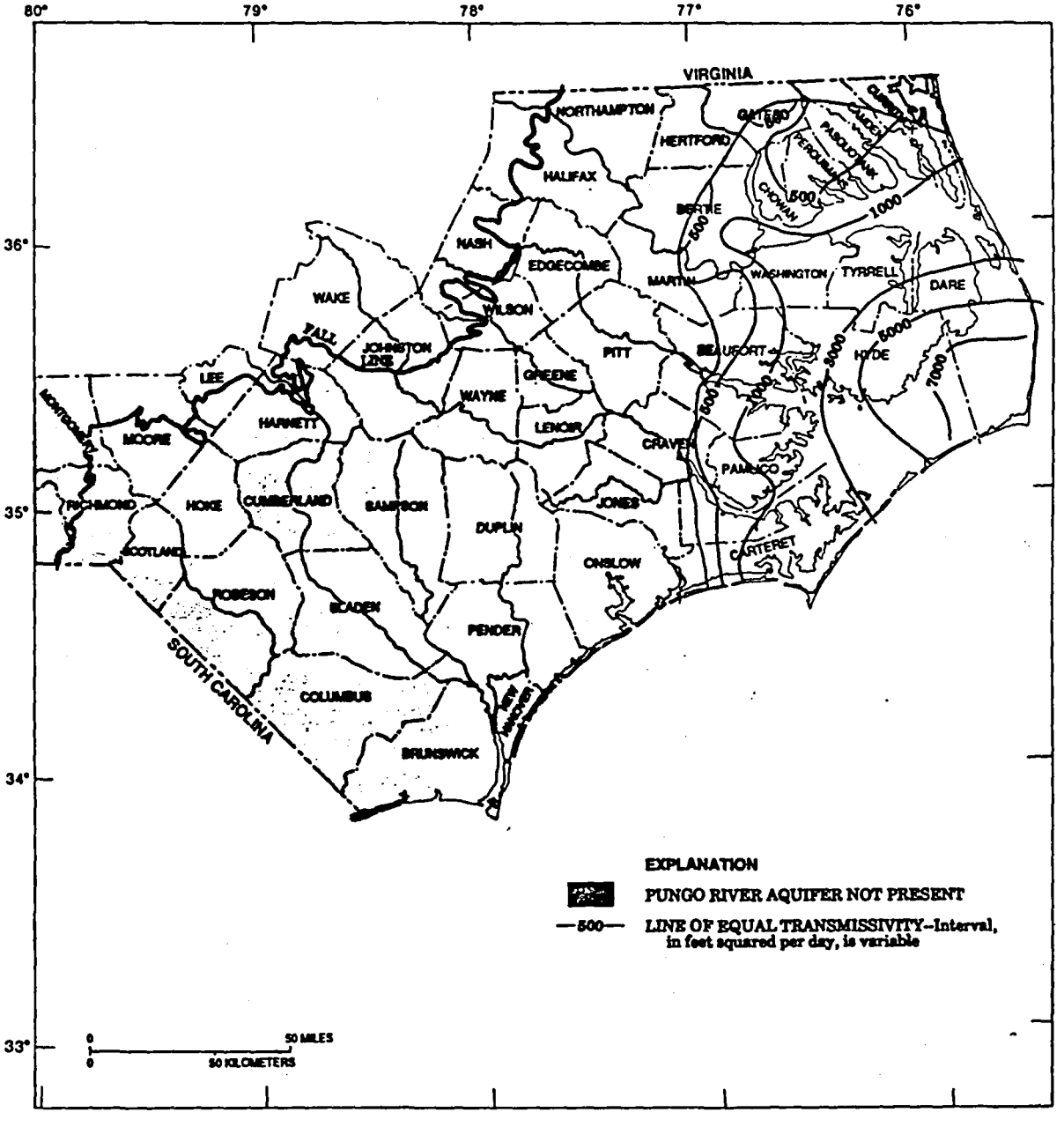


Figure 27.--Transmissivity of the Pungo River (A8) used in model simulations.

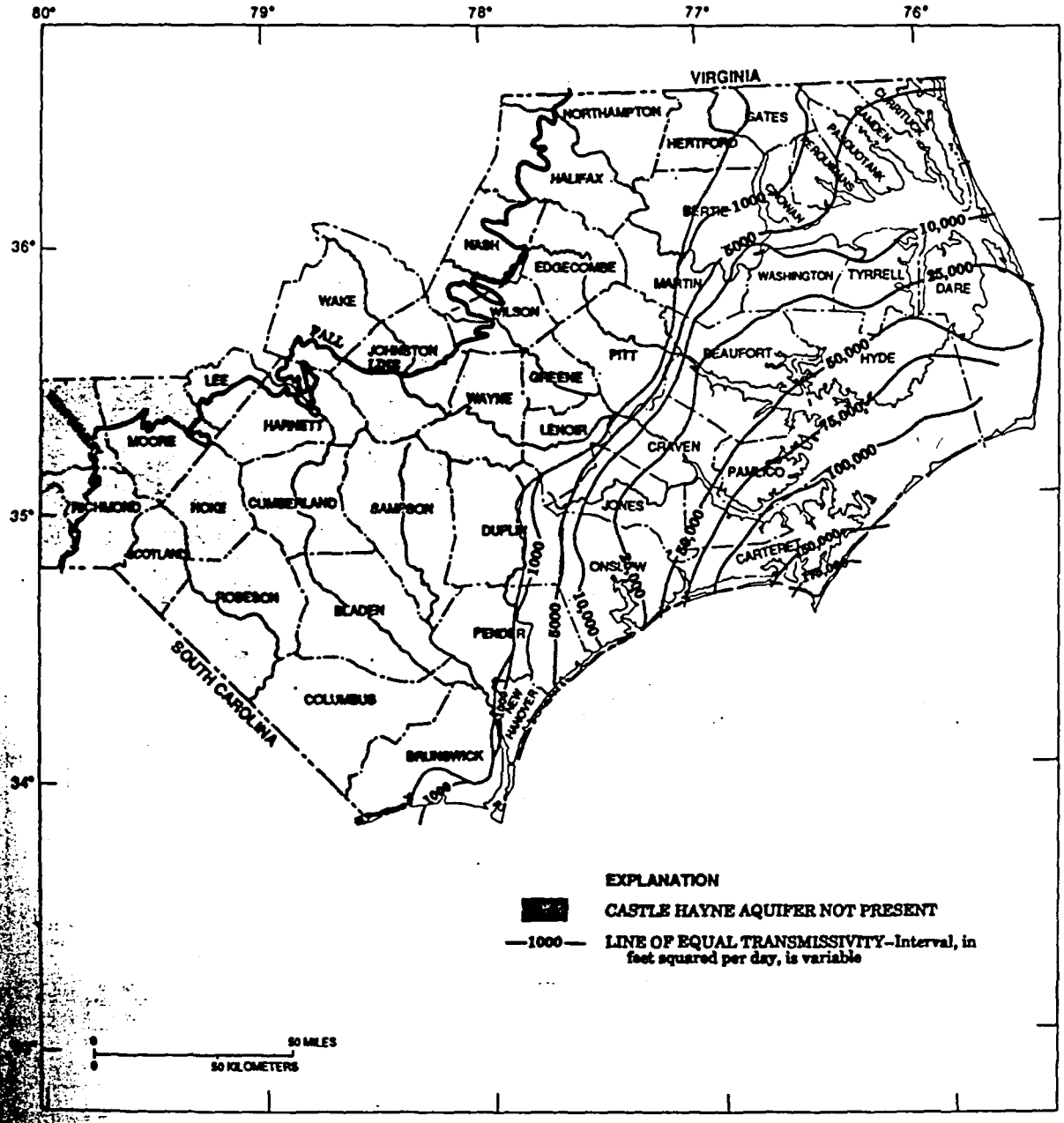


Figure 28.--Transmissivity of the Castle Hayne aquifer (A7) used in model simulations.

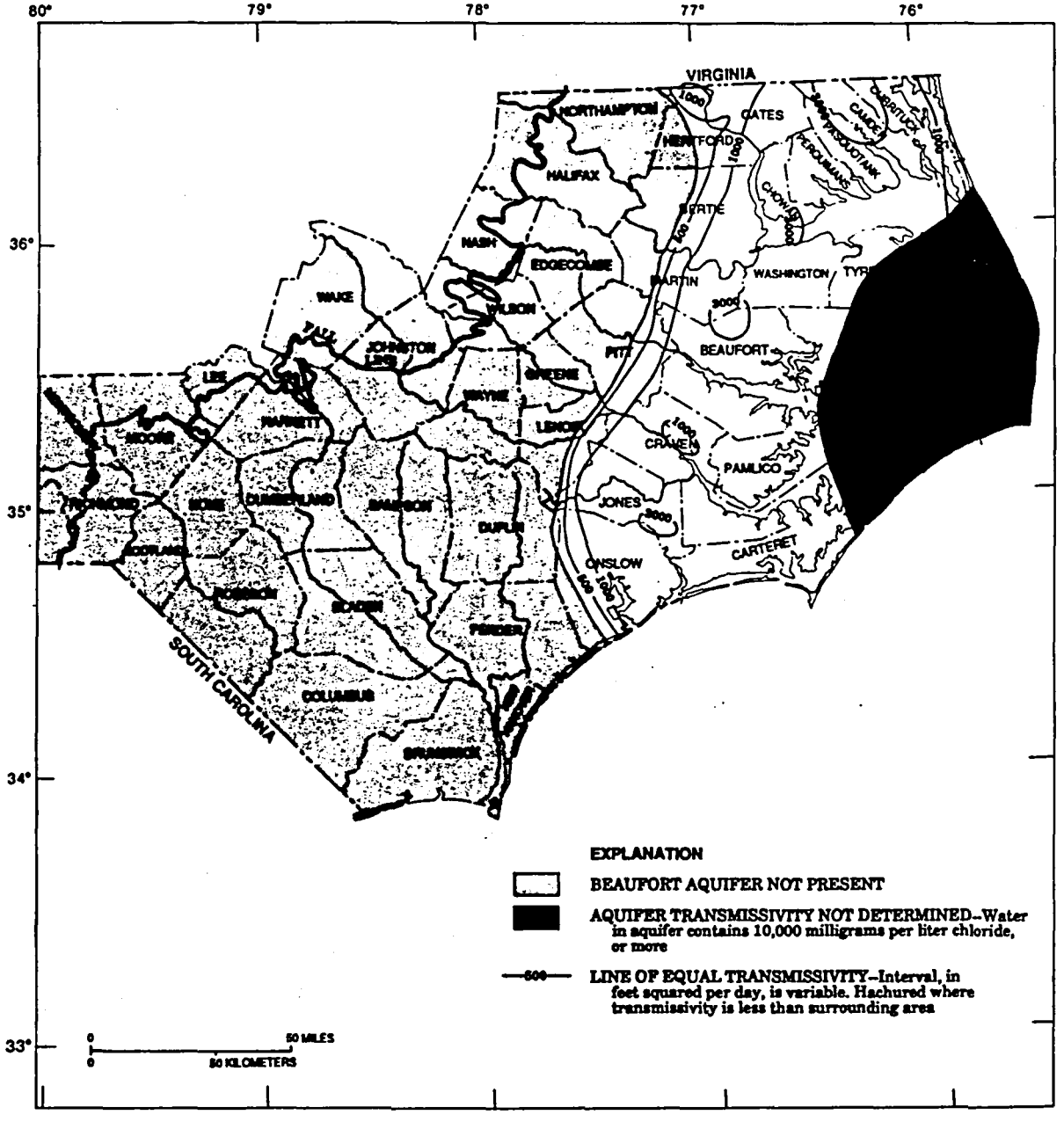


Figure 29.--Transmissivity of the Beaufort aquifer (A6) used in model simulations.

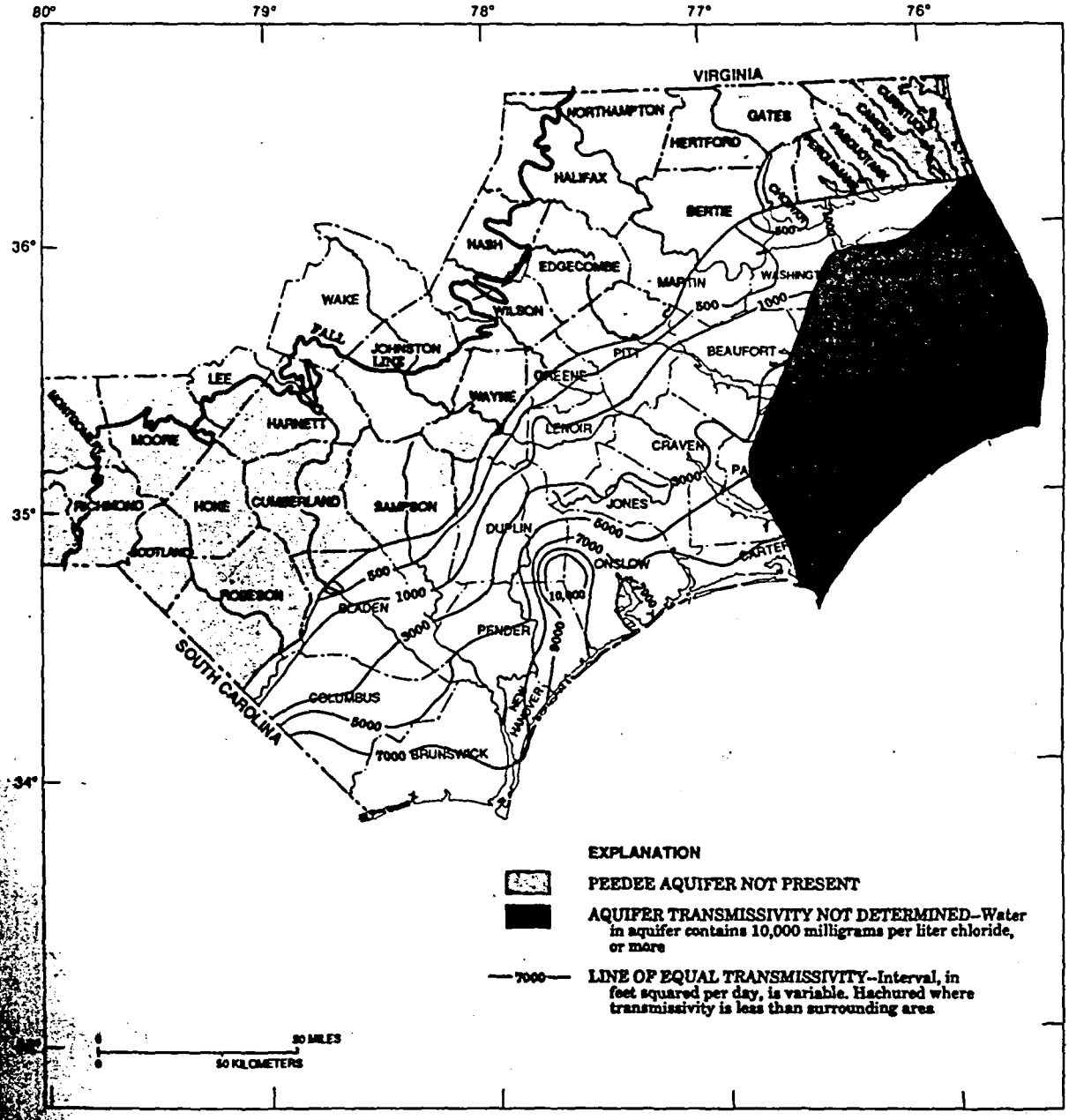


Figure 30.--Transmissivity of the Peedee aquifer (A5) used in model simulations.

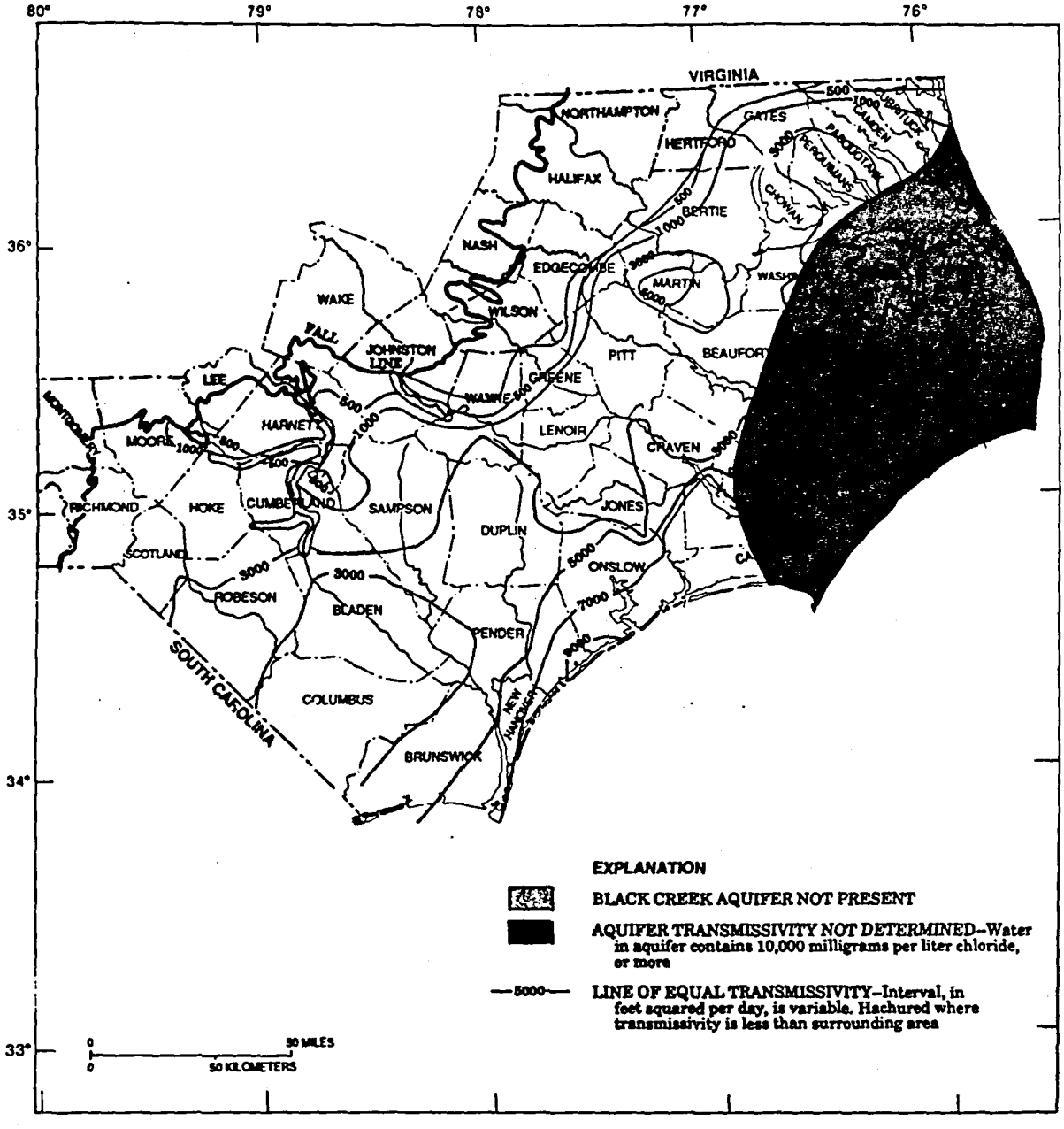


Figure 31.--Transmissivity of the Black Creek aquifer (A4) used in model simulations.

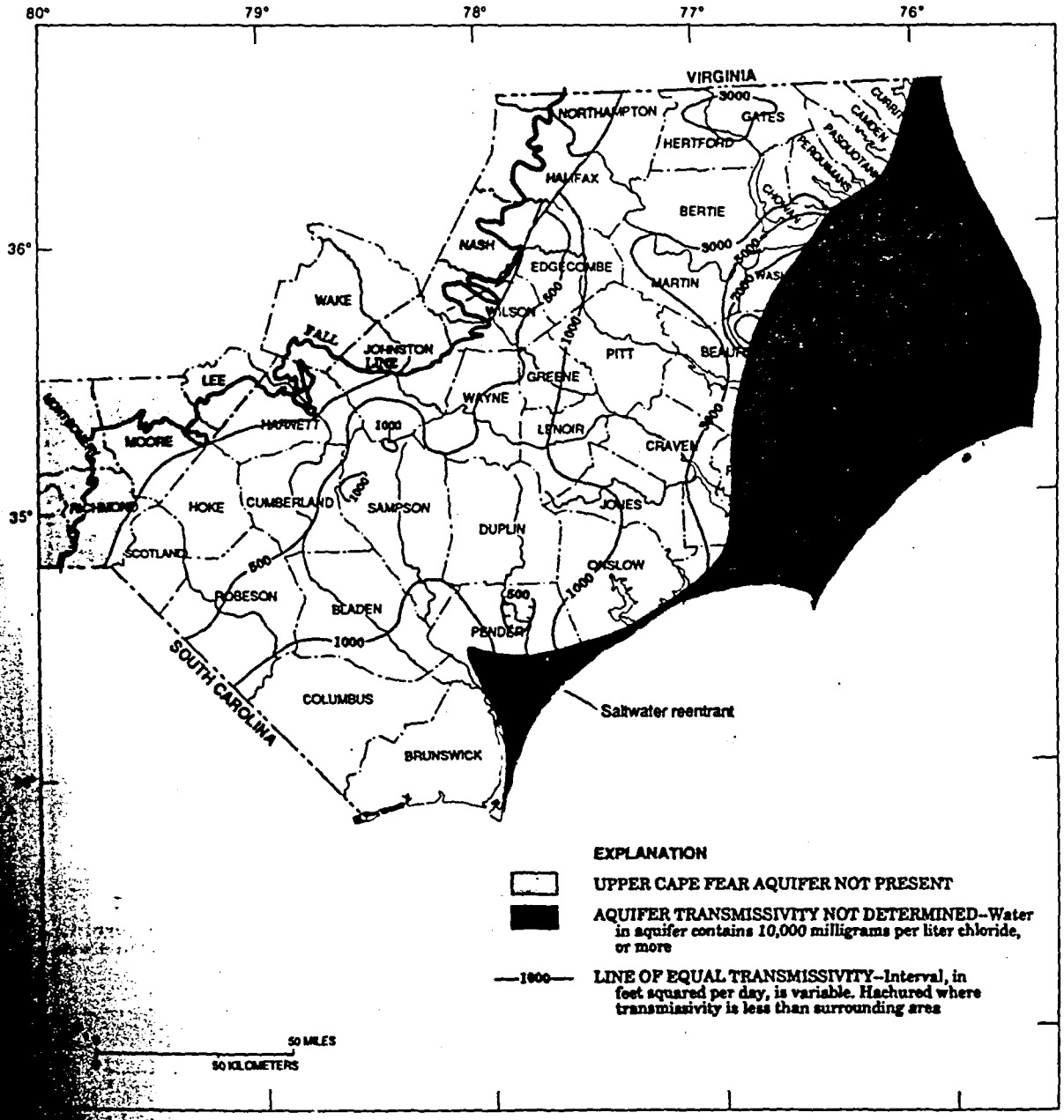


Figure 32.--Transmissivity of the upper Cape Fear aquifer (A3) used in model simulations.

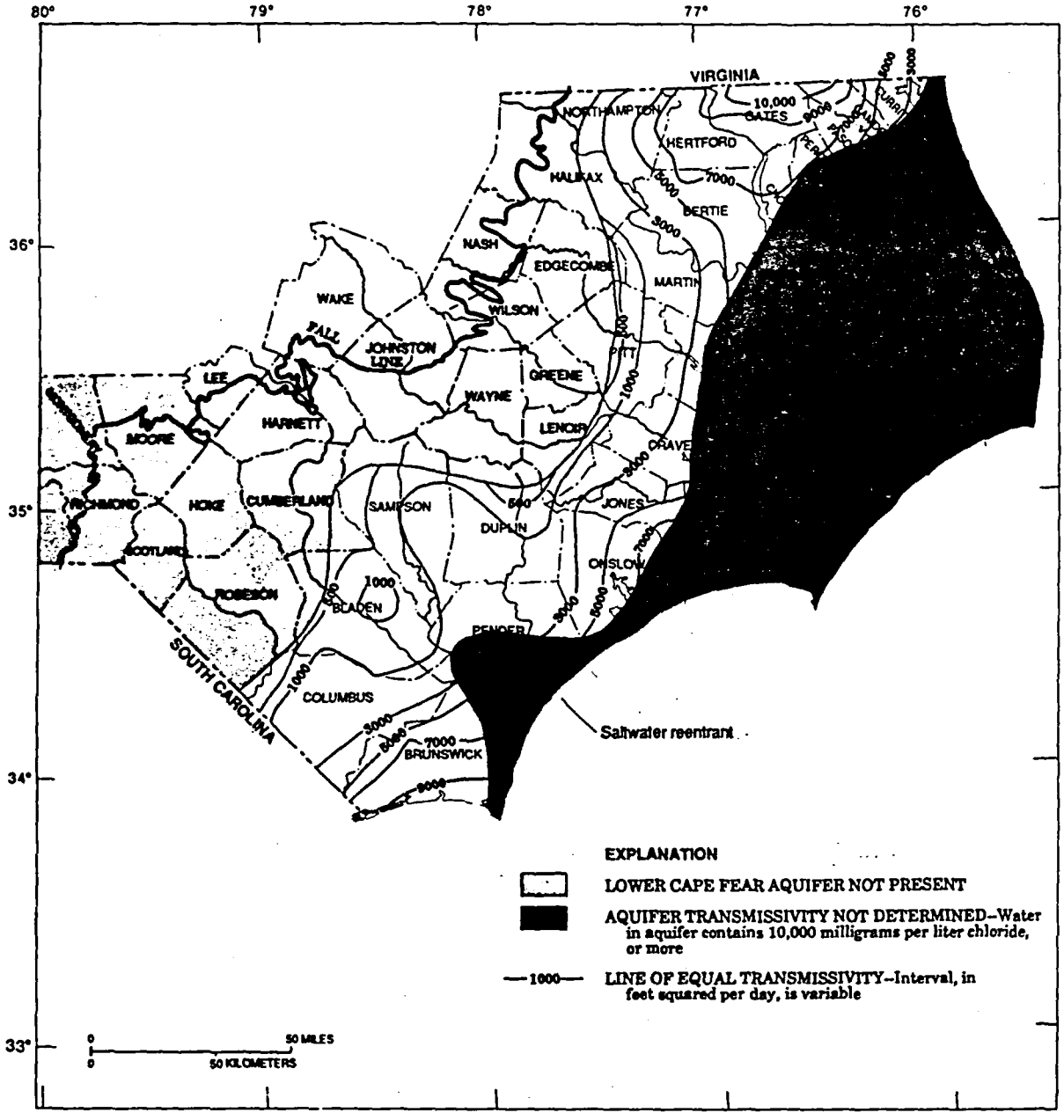


Figure 33.--Transmissivity of the lower Cape Fear aquifer (A2) used in model simulations.

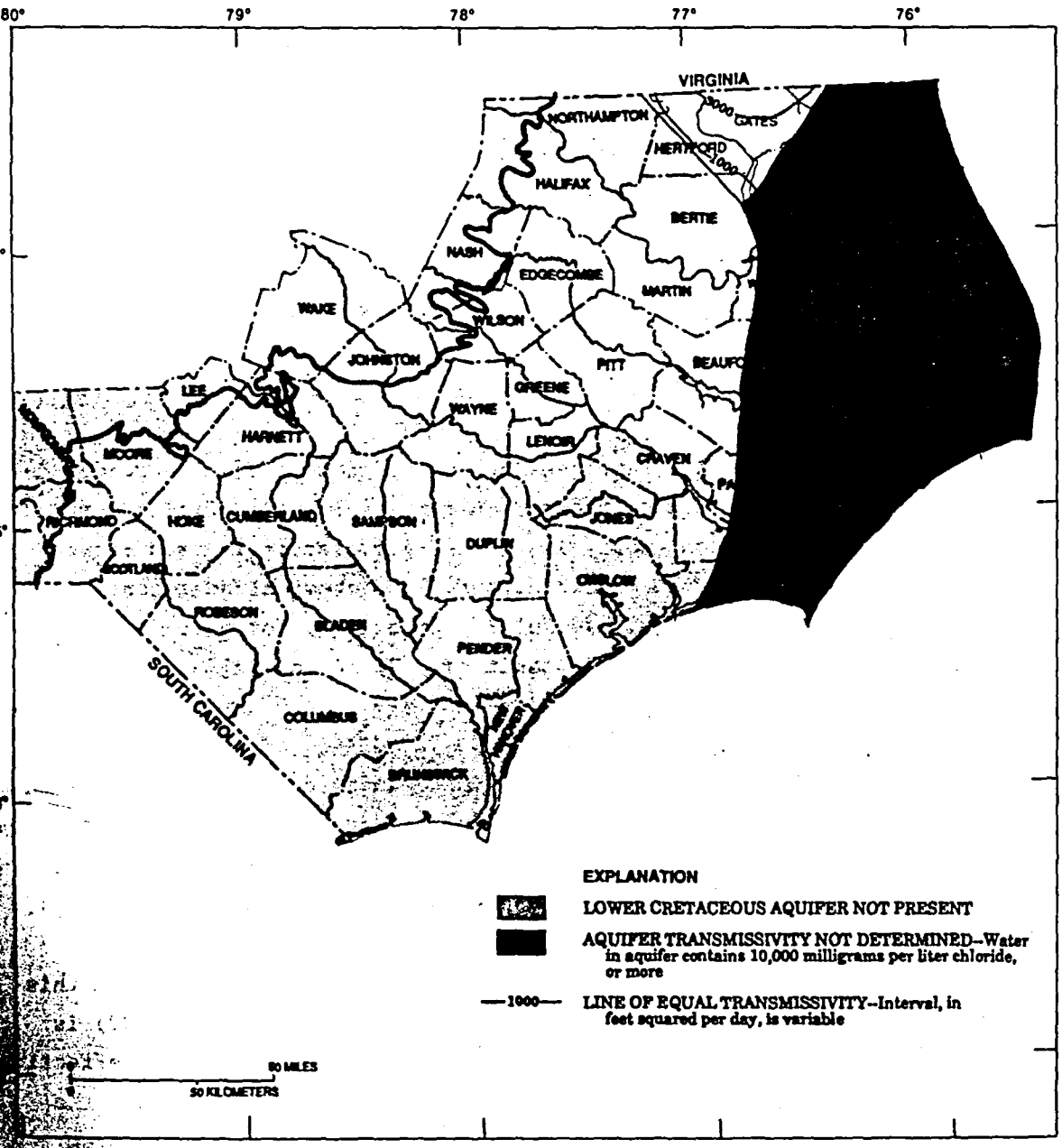


Figure 34.--Transmissivity of the Lower Cretaceous aquifer (A1) used in model simulations.

As previously mentioned, the model assumes all flow in aquifers to be horizontal and all flow in confining units to be vertical. It was recognized, however, that in many places within zones designated as aquifer material, the thickness of clay is significant, and this clay often functions as an impediment to vertical flow. A more realistic simulation of the flow system was obtained by incorporating the effects of clay within aquifers into the leakance terms. Accordingly, total effective thickness (b) values for each confining unit were generated (figs. 35-43) which represented the sum of (1) effective confining unit thickness, (2) one-half the thickness of clay beds in the aquifer above the confining unit, and (3) one-half the thickness of clay beds in the aquifer below the confining unit. At some locations shown in figures 35-43 where the confining unit is designated as not present (particularly in stream valleys), the clay within aquifers concept was used to assign an effective clay thickness for modeling purposes.

Initial values for K_v, representing the vertical hydraulic conductivity of confining unit material, were based on appraisals of confining unit effectiveness derived from geophysical logs, differences in head between aquifers above and below the confining unit, and chemical analyses, using as a guideline values of vertical hydraulic conductivity for various materials given by Morris and Johnson (1967, table 6). These initial values ranged from 1×10^{-3} ft/day to 4×10^{-6} ft/day.

At many locations, two or more confining units need to be considered for modeling purposes as occurring between two non-sequential aquifers (case A in fig. 44). For example, the lower Cape Fear aquifer (A2) may be present and directly above it the lower and upper Cape Fear confining unit (CU2), and the Black Creek aquifer (A4) may be present. The upper Cape Fear aquifer (A3) and upper Cape Fear confining unit (CU3) are missing in this example. In this situation the lower Cape Fear confining unit (CU2) is considered as being composed of two confining units: half of the effective thickness belonging to the lower Cape Fear confining unit (CU2) and the other half belonging to the upper Cape Fear confining unit (CU3), even though the upper Cape Fear confining unit (CU3) is not present. In general, the confining unit is divided into N + 1 equal parts, where N is the number of missing aquifers. Although the transmissivity of the missing aquifers is

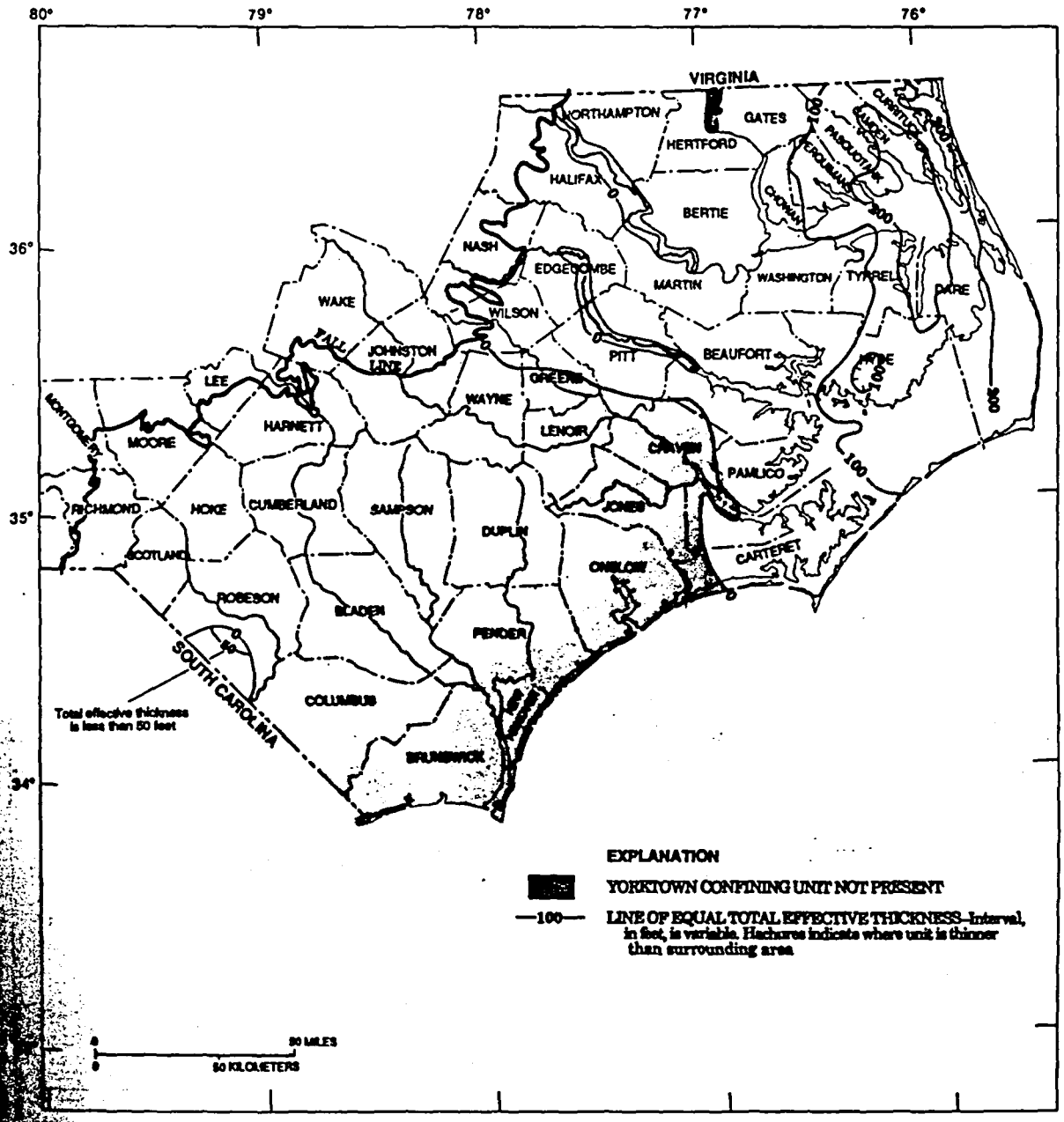


Figure 35.--Effective thickness of the Yorktown confining unit (CU9).

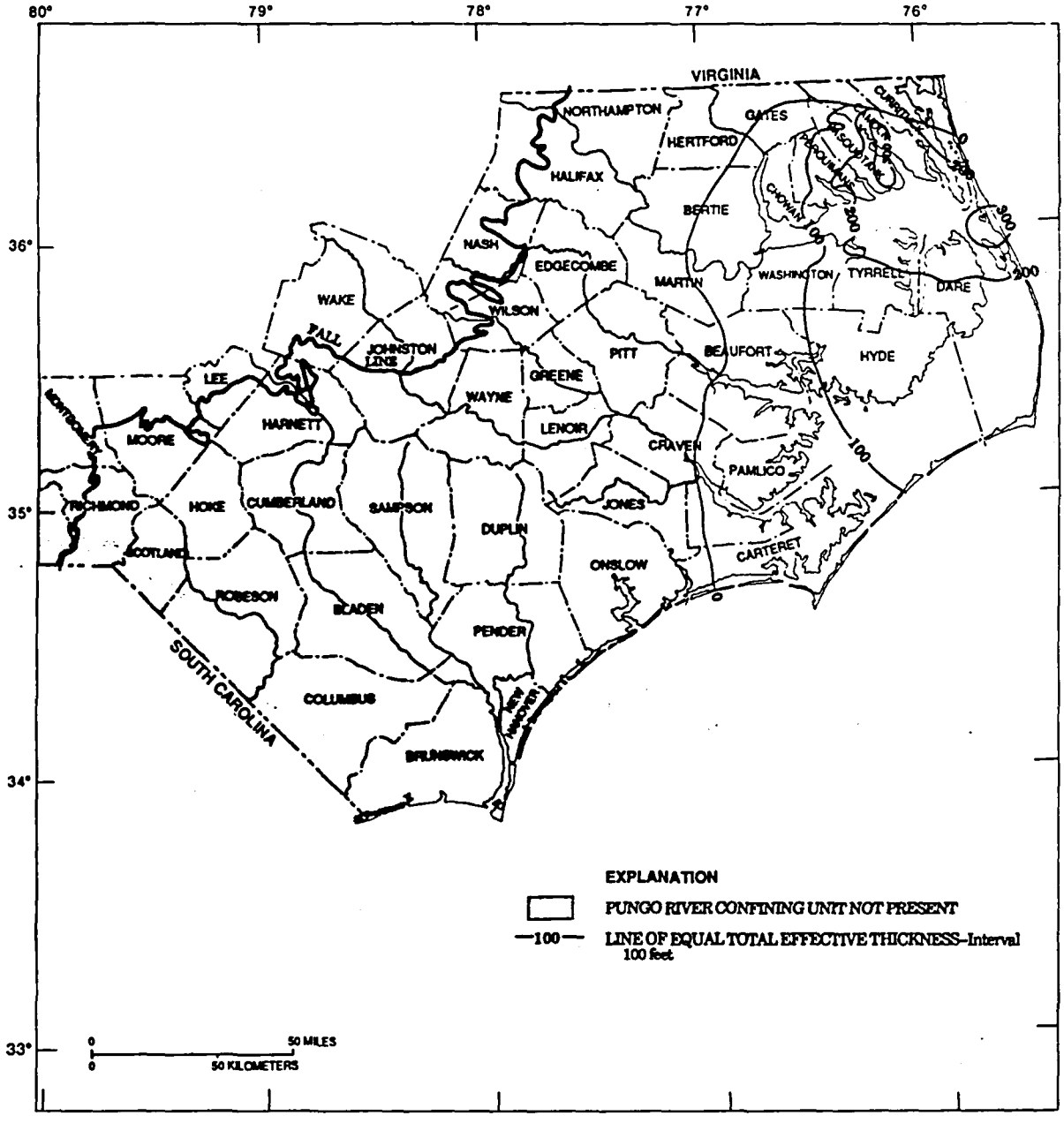
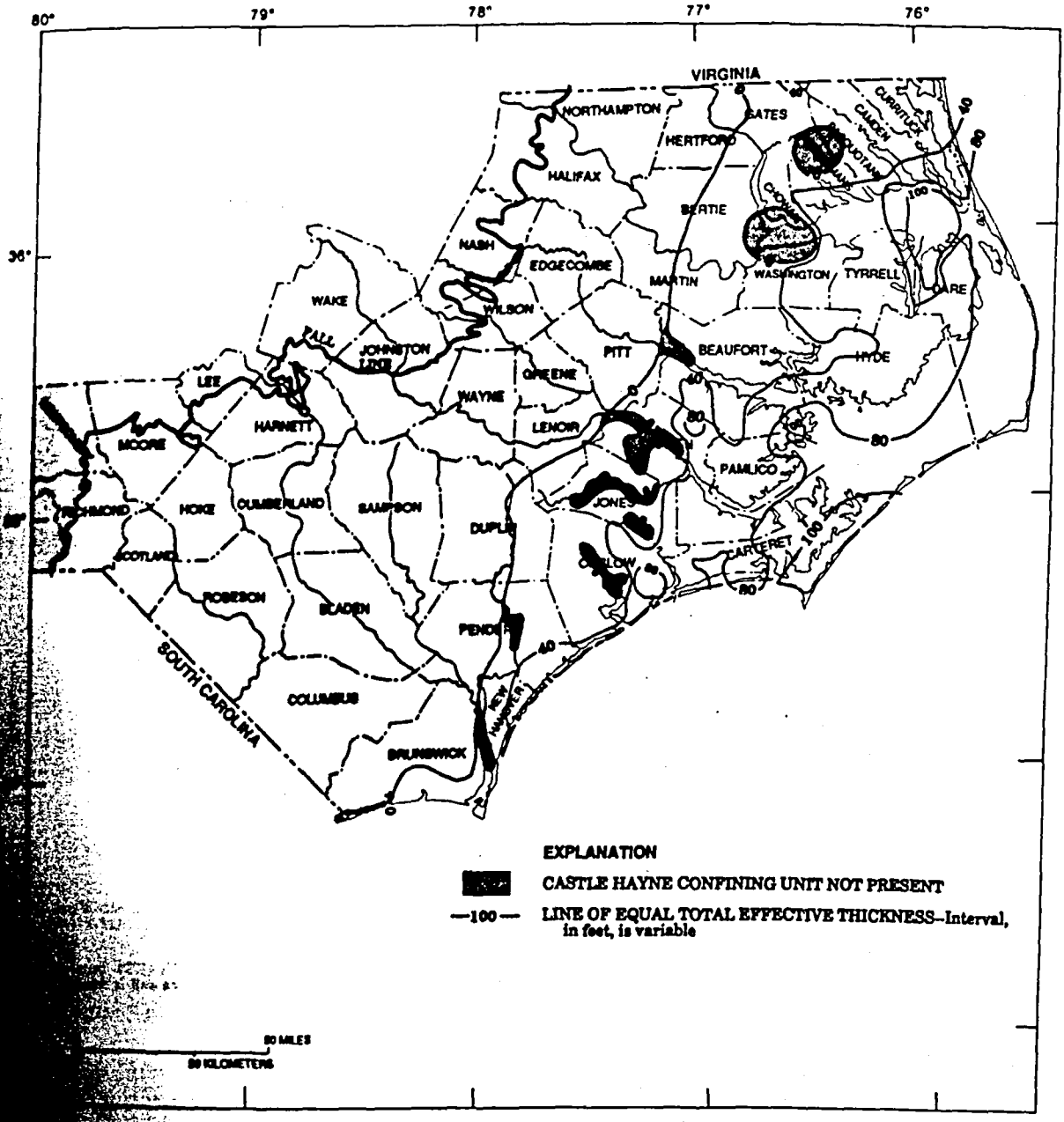


Figure 36.--Effective thickness of the Pungo River confining unit (CU8).



37.--Effective thickness of the Castle Hayne confining unit (CU7).

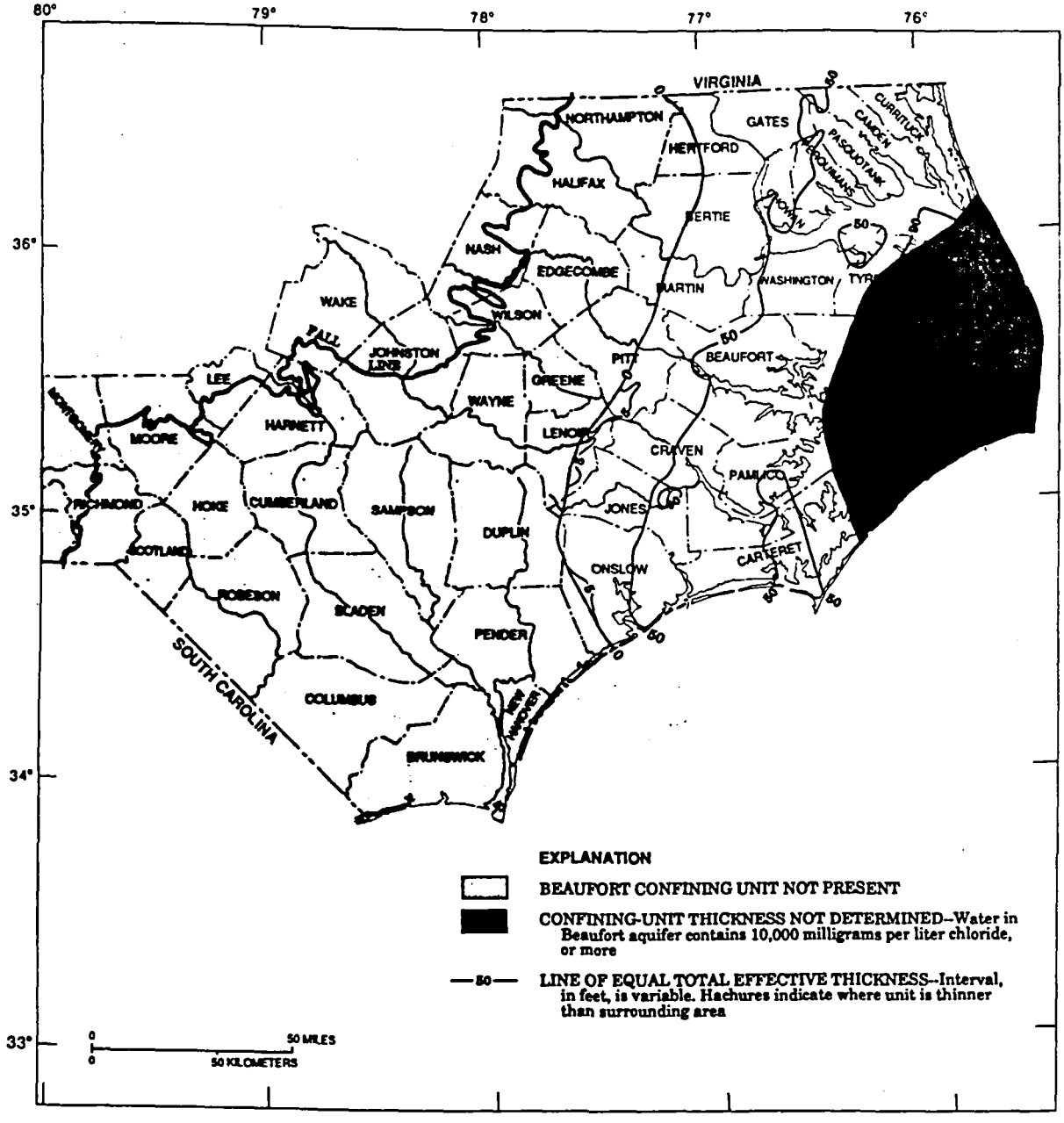


Figure 38.--Effective thickness of the Beaufort confining unit (CU6).

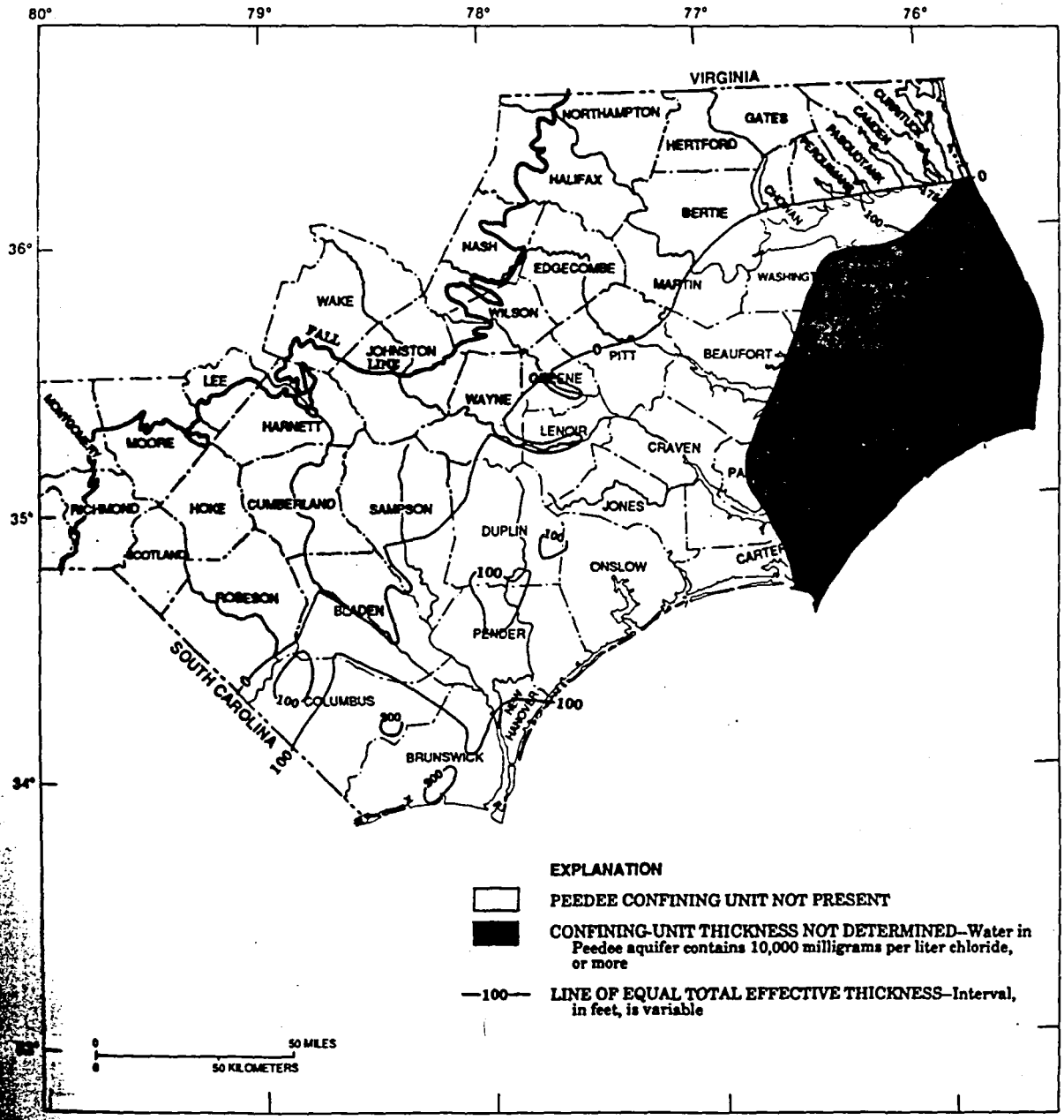


Figure 39.--Effective thickness of the Peedee confining unit (CU5).

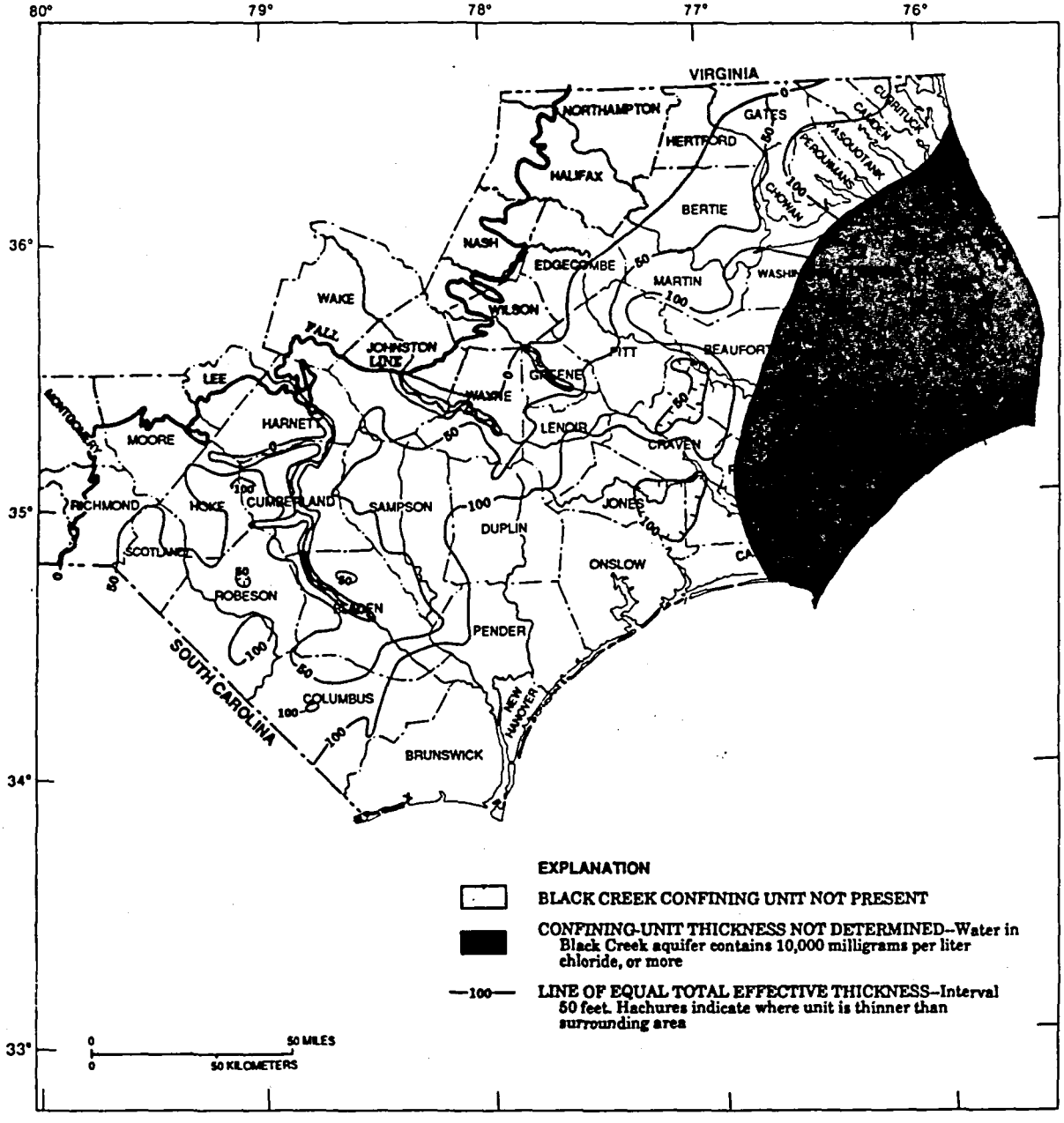


Figure 40.--Effective thickness of the Black Creek confining unit (CU4).

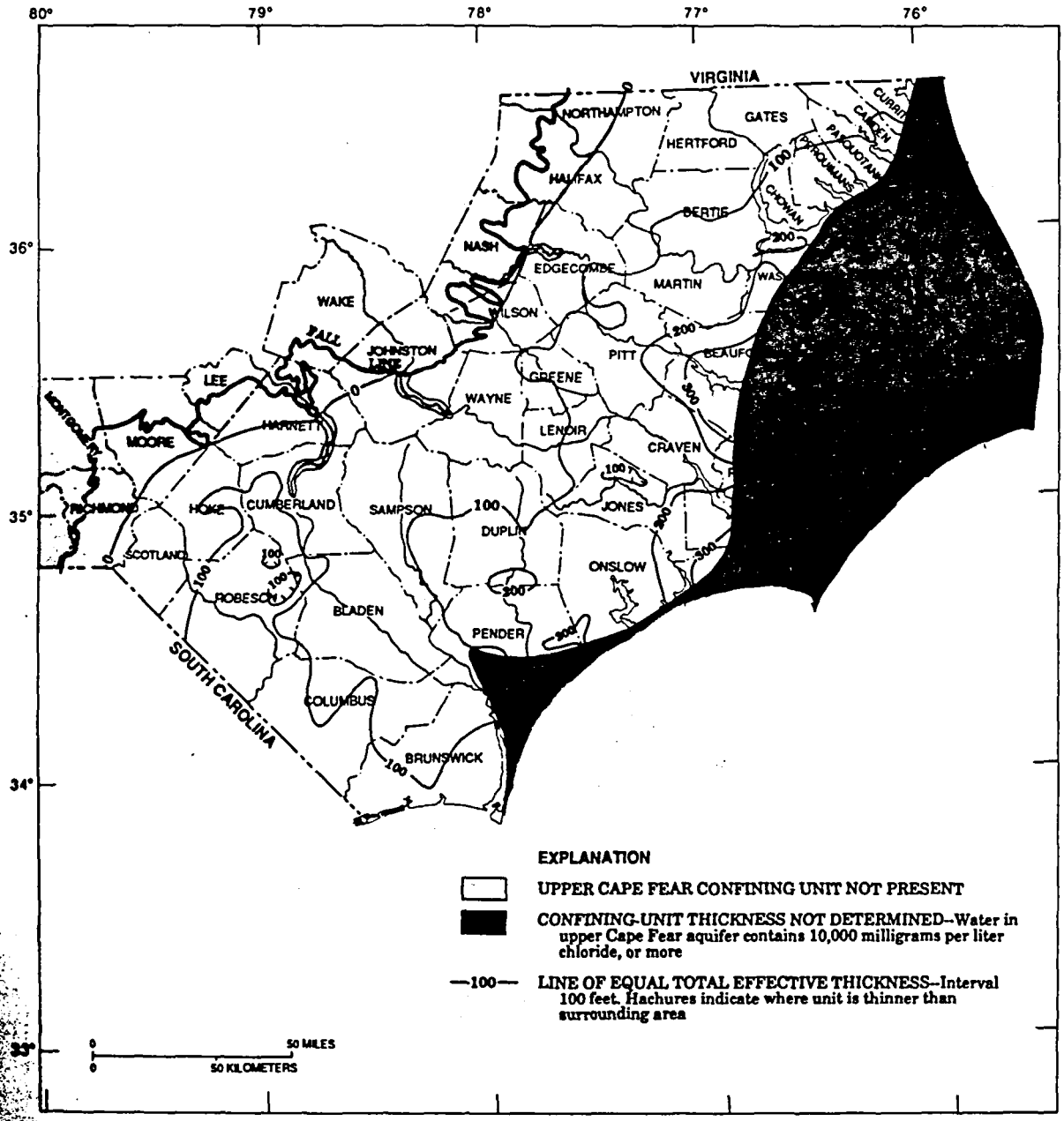


Figure 41.--Effective thickness of the upper Cape Fear confining unit (CU3).

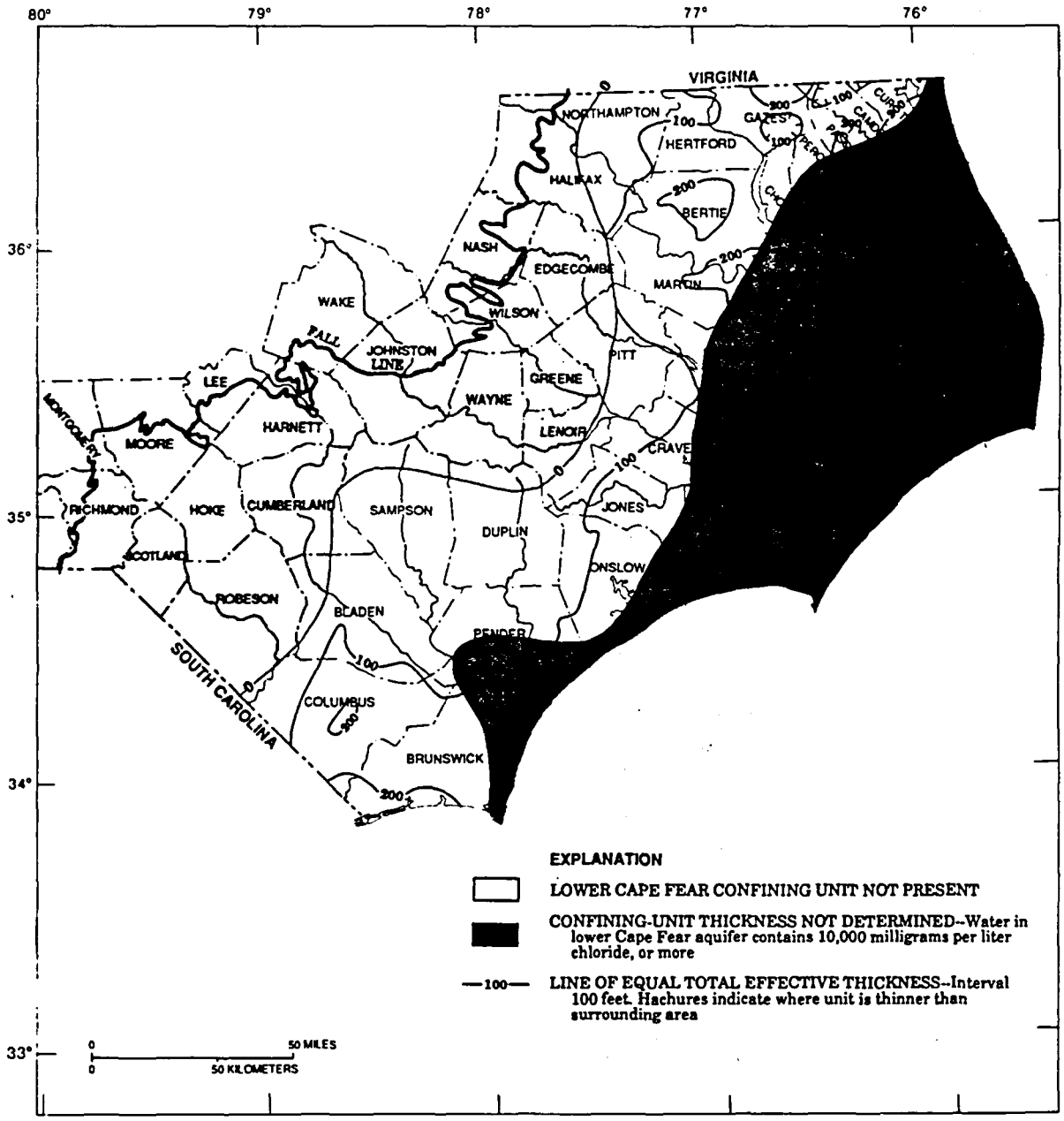


Figure 42.--Effective thickness of the lower Cape Fear confining unit (CU2).

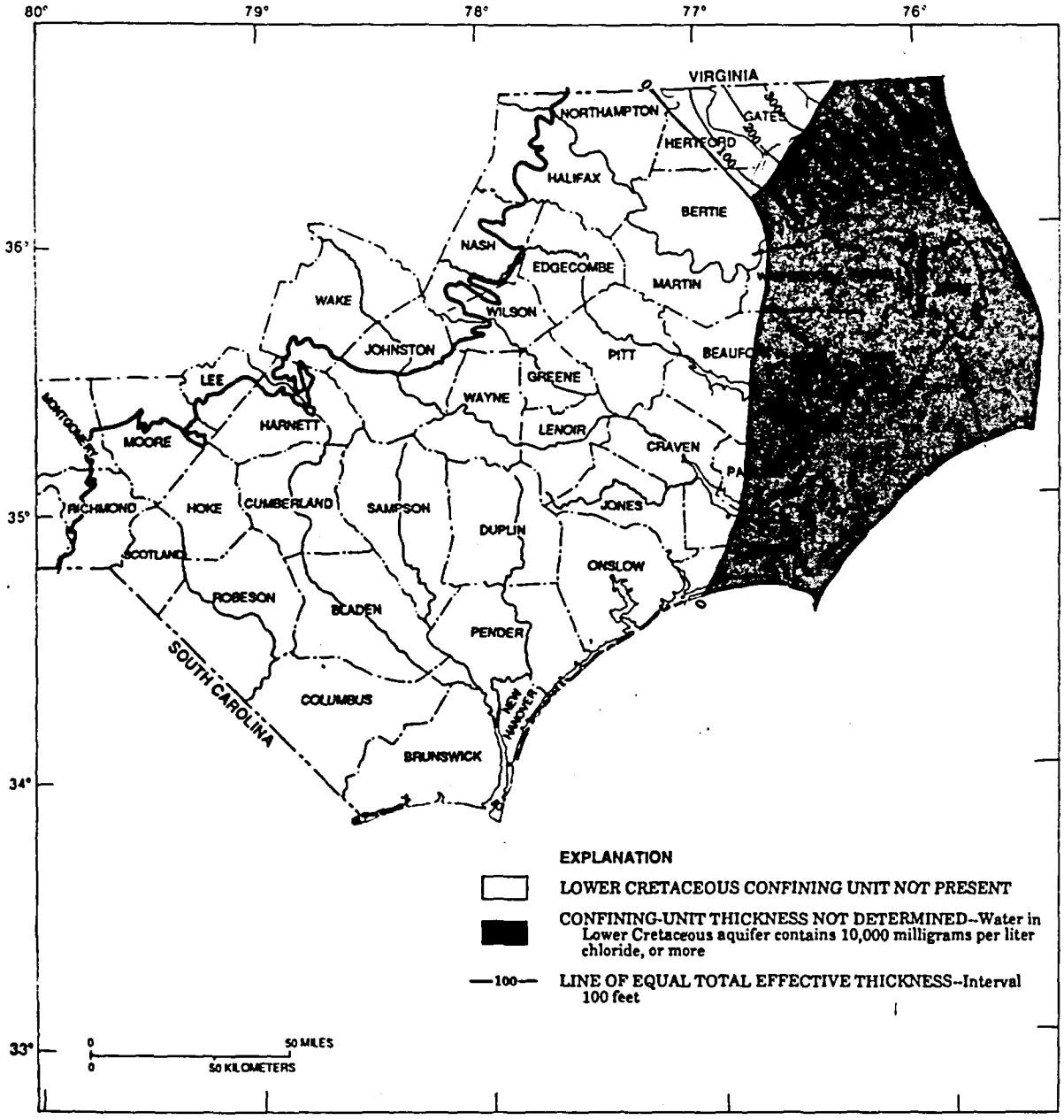


Figure 43.--Effective thickness of the Lower Cretaceous confining unit (CU1).

zero at these locations and no horizontal flow can occur, the modified version of the Trescott flow model used in this study (described in detail by Leahy, 1982) allows for vertical movement of water at these locations.

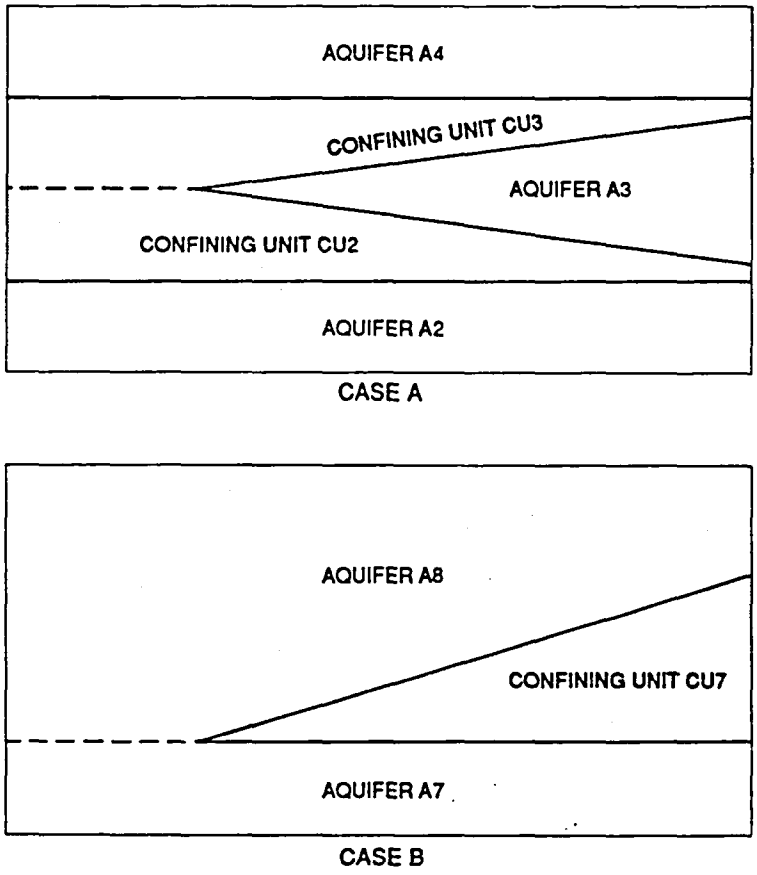


Figure 44.--Schematic diagram illustrating aquifer or confining unit pinchout as applied to model structure.

The opposite situation is where a confining unit is missing and two aquifers are in direct contact (case B in fig. 44). This condition was simulated by arbitrarily assigning small confining unit thicknesses ranging from 0.01 to 0.001 ft. This occurs mostly in stream valleys where the surficial aquifer (A10) is in direct contact with an underlying aquifer and results in high leakance values. A notable exception is in the western Pamlico Sound area, where the Pungo River aquifer (A8) is in direct contact with the underlying Castle Hayne aquifer (A7).

The leakance (TK) values for the confining units from the calibrated model are shown in figures 45 through 53. The rationale for varying leakance values during calibration is discussed in the "Model Calibration" section later in this report.

Ground-water withdrawals and time discretization

In order to simulate the behavior of the North Carolina Coastal Plain aquifer system through time, it was necessary to develop pumpage histories for major ground-water users, that is users who withdraw 100,000 gal/d (gallons per day) or more. This information was gathered primarily from interviews with personnel of public-supply systems and self-supplied industries during 1982-83 and was supplemented by existing reports and data of the U.S. Geological Survey (Robison (1977) and Robison and Mann (1977)), the North Carolina Department of Environment, Health, and Natural Resources, formerly called the North Carolina Department of Natural Resources and Community Development (North Carolina Department of Natural Resources and Community Development, 1983), and the North Carolina Department of Human Resources.

Withdrawals by more than 115 public supplies and industries included in the survey exceeded 195 Mgal/d in 1980, doubling about every decade since 1940 (fig. 54). The largest single user is a phosphate-mining and chemical-production operation in Beaufort County, which began withdrawals in 1965 at a rate of 31 Mgal/d. By 1980, withdrawals for this operation had leveled off at a rate of about 64 Mgal/d. Sharp declines in pumpage in 1944, 1945, 1961, and 1964 are entirely due to decreases in pumpage at two rock quarries in Onslow and Craven Counties; sharp increases in 1945 and 1958 are due to pumpage increases at these same two quarries.

To simulate the flow system over time, the period from January 1, 1900, to January 1, 1981, was divided into 10 time periods; within each period pumpage is treated as a constant. The 10 time periods chosen are listed on page 81.

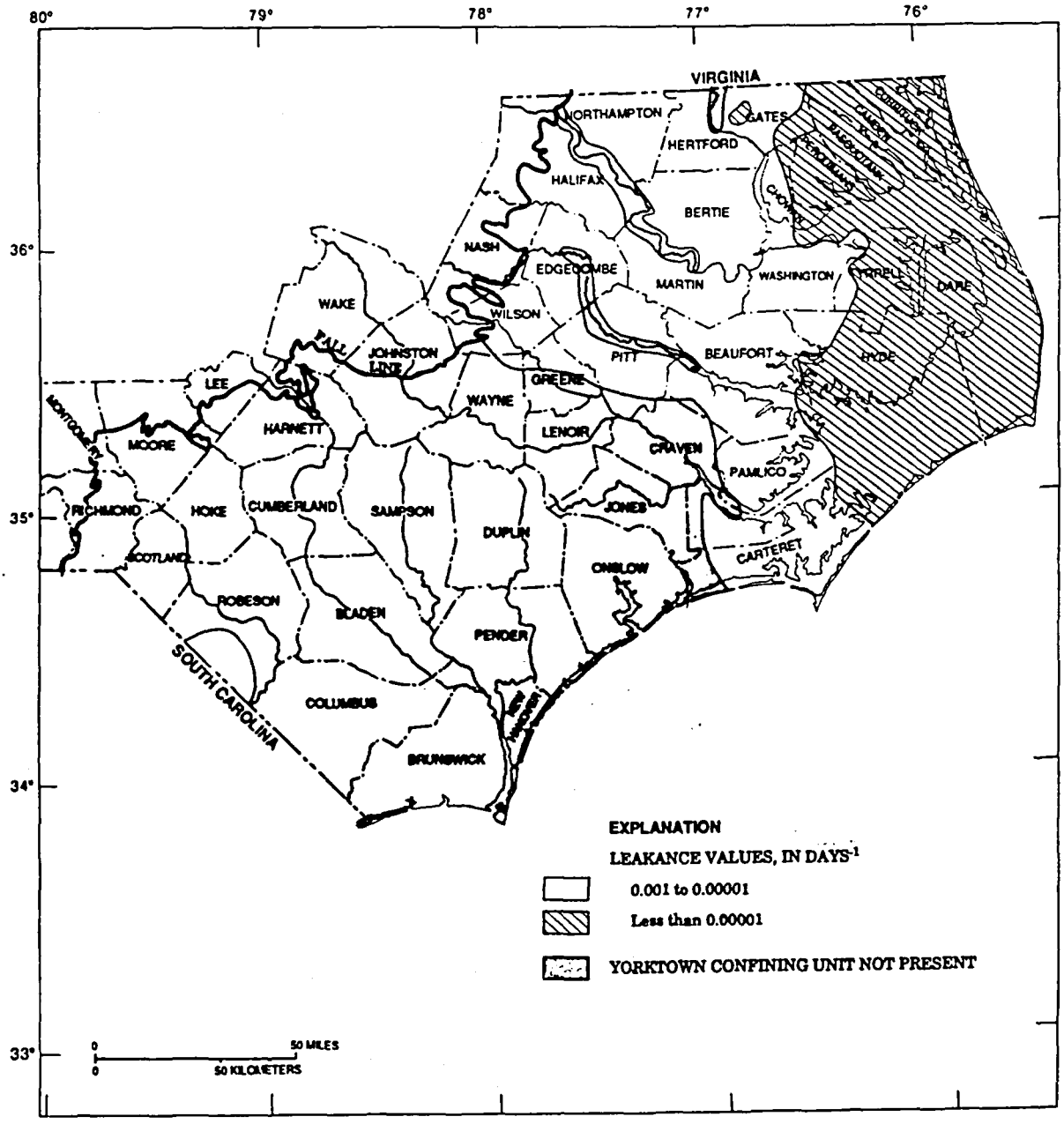


Figure 45.--Model-derived leakance (TK) of the Yorktown confining unit (CU9).

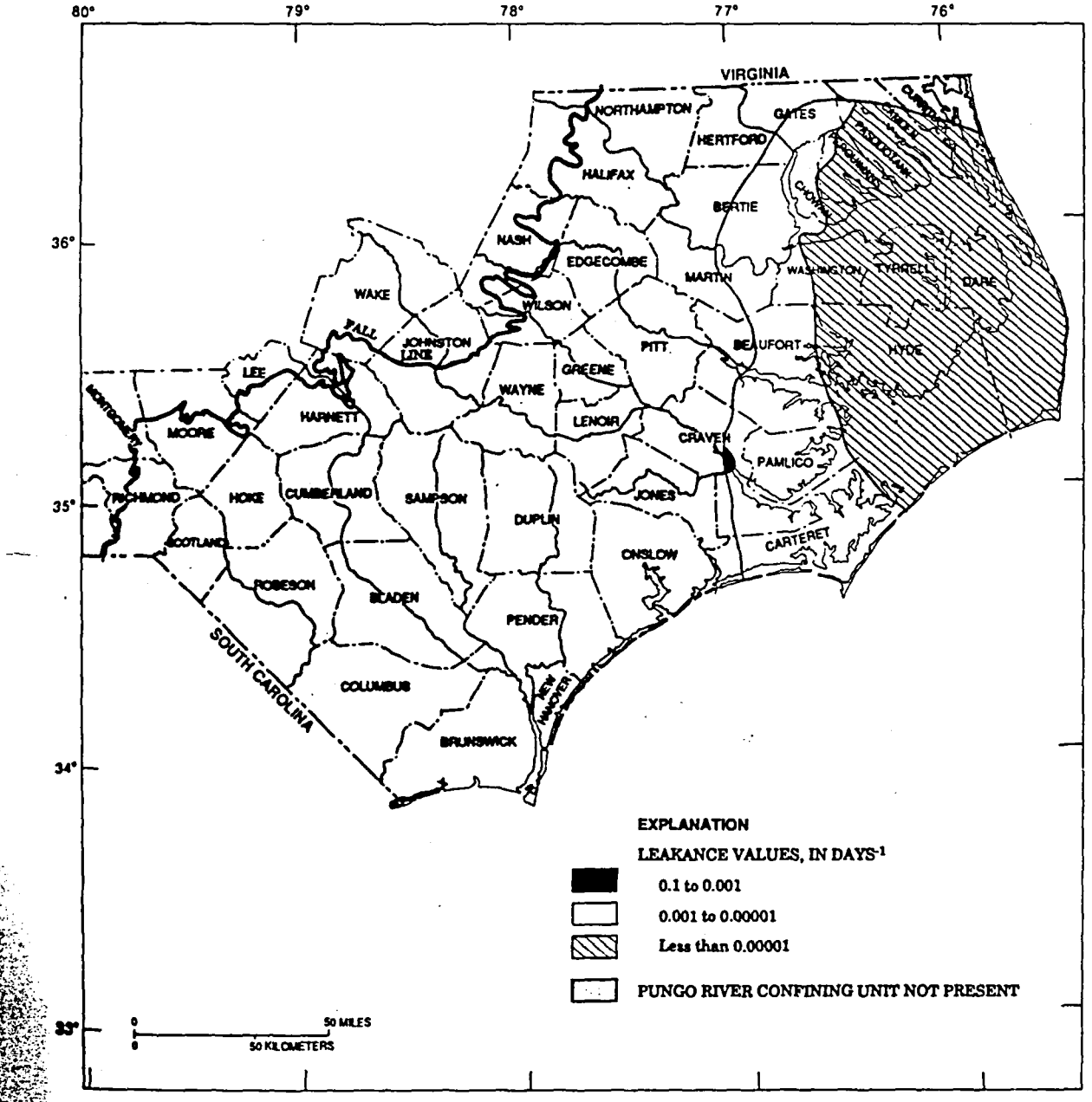


Figure 46.--Model-derived leakance (TK) of the Pungo River confining unit (CU8).

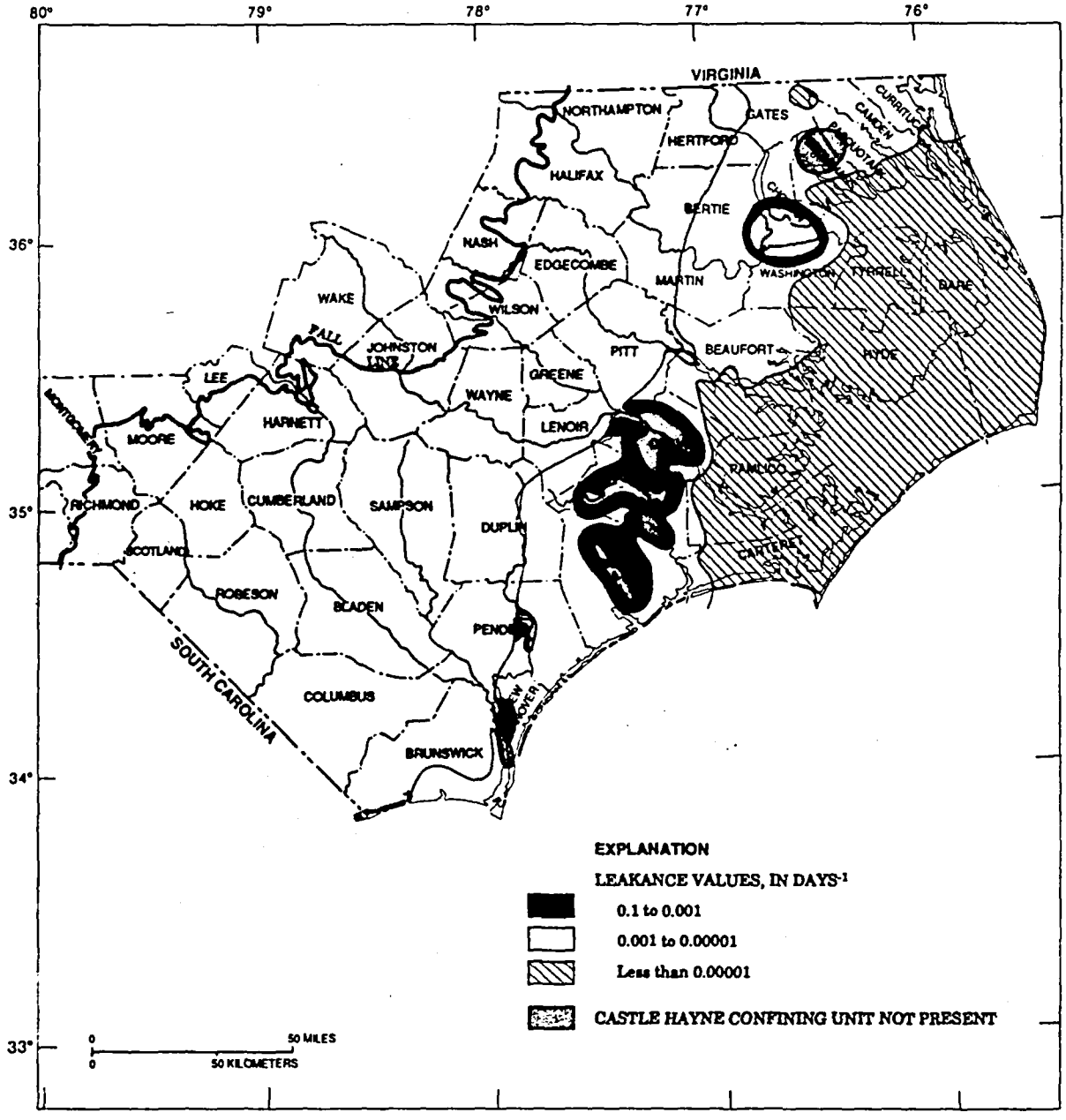


Figure 47.--Model-derived leakance (TK) of the Castle Hayne confining unit (CU7).

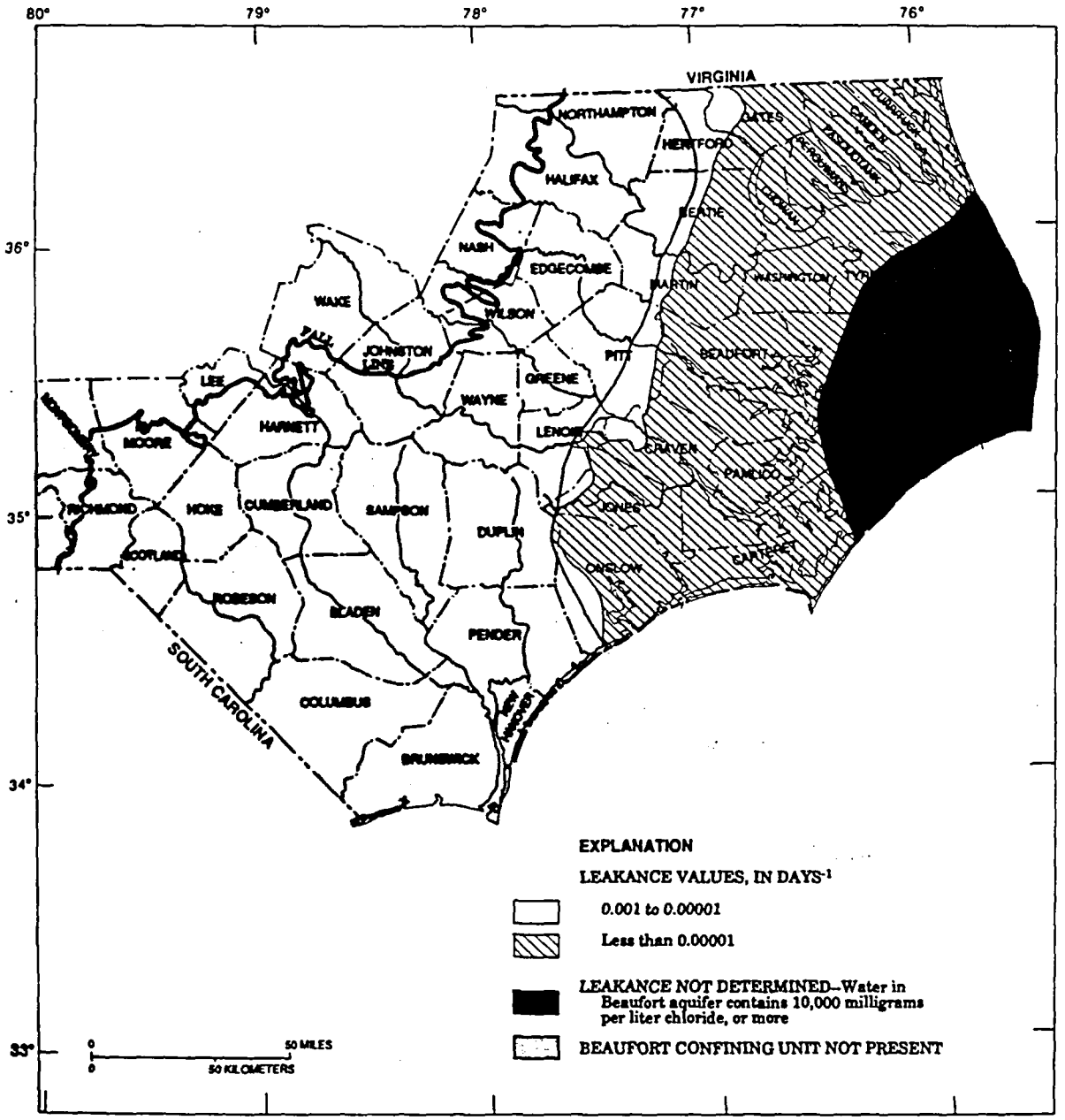


Figure 48.--Model-derived leakance (TK) of the Beaufort confining unit (CU6).

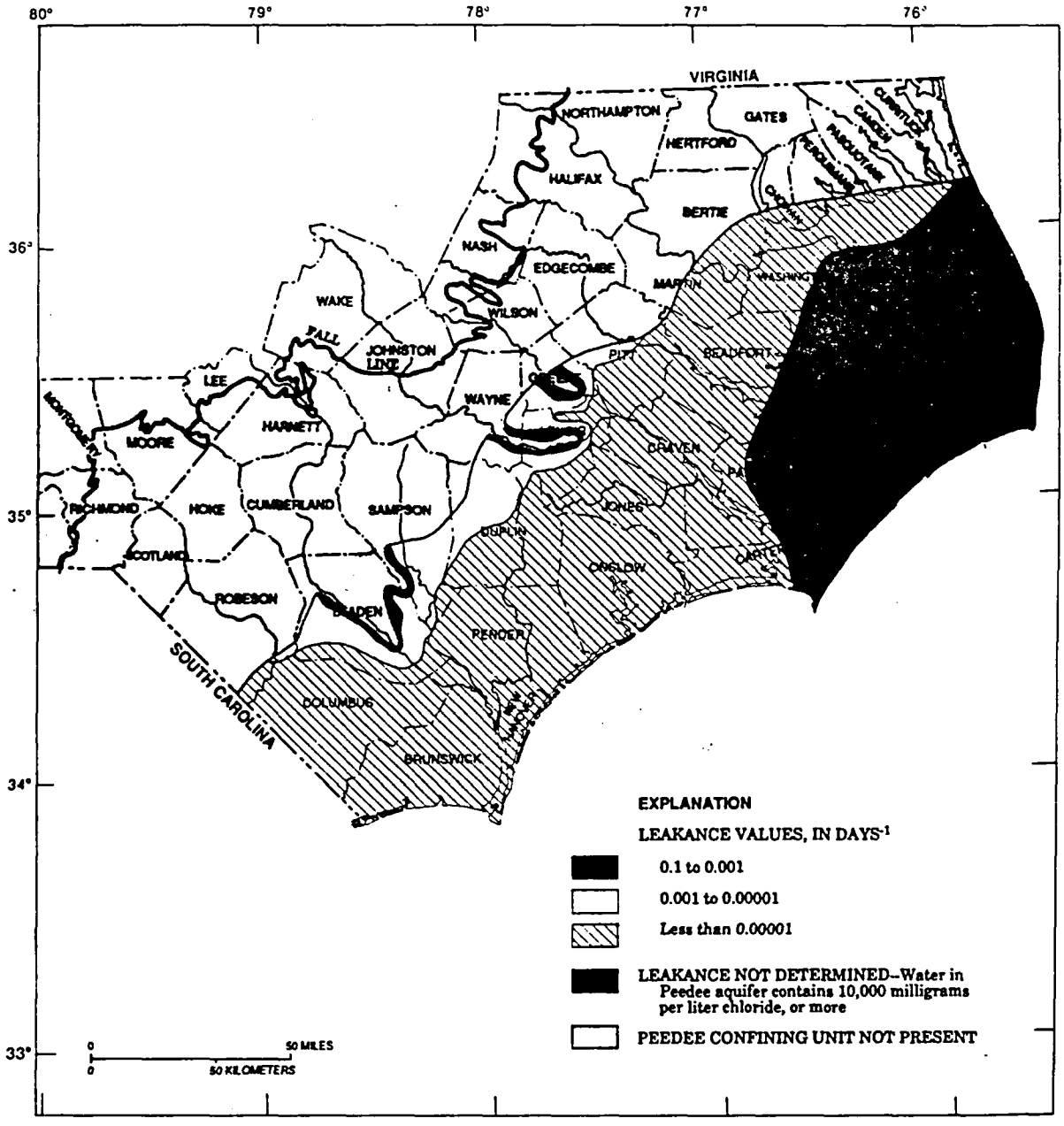


Figure 49.--Model-derived leakance (TK) of the Peedee confining unit (CU5).

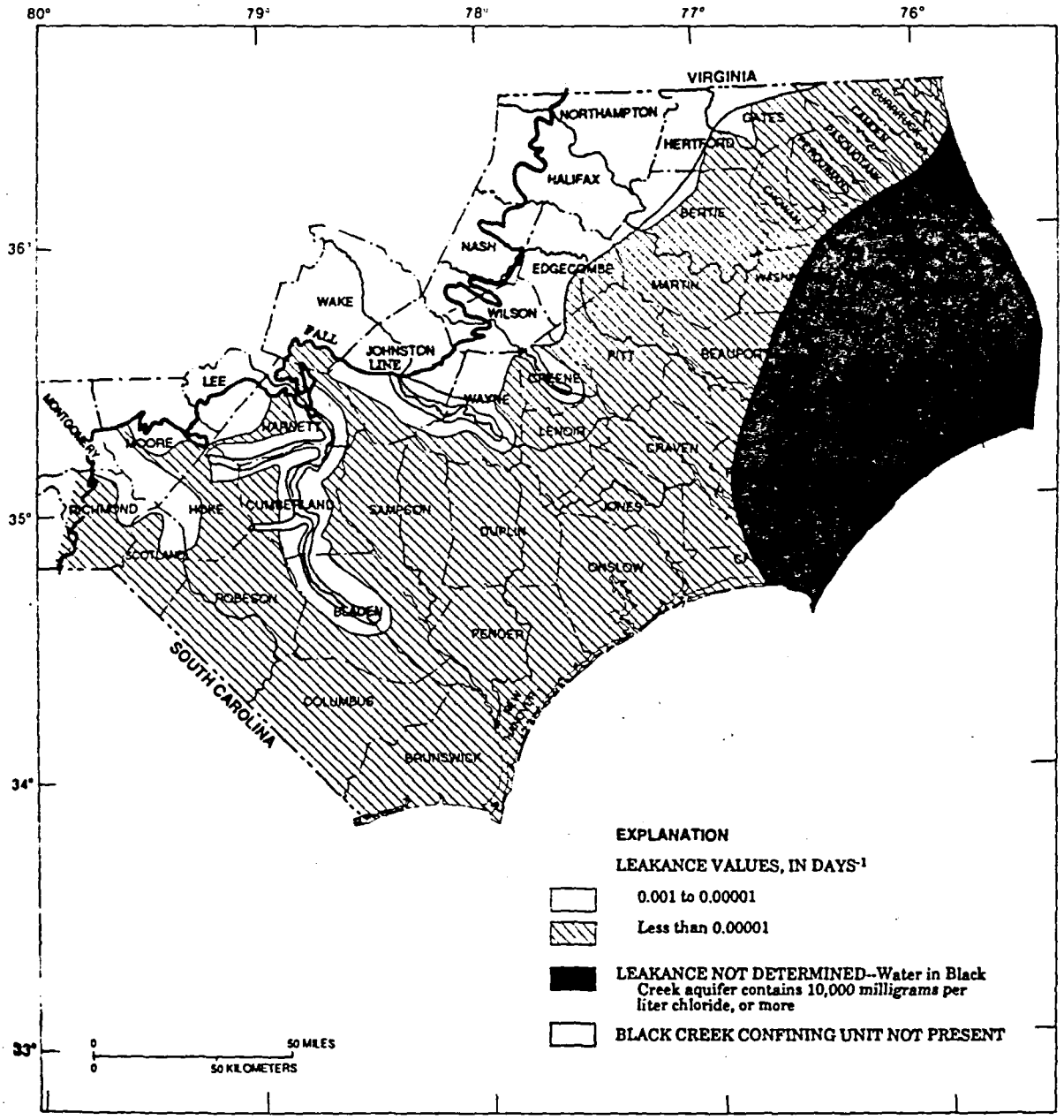


Figure 50.--Model-derived leakance (TK) of the Black Creek confining unit (CU4).

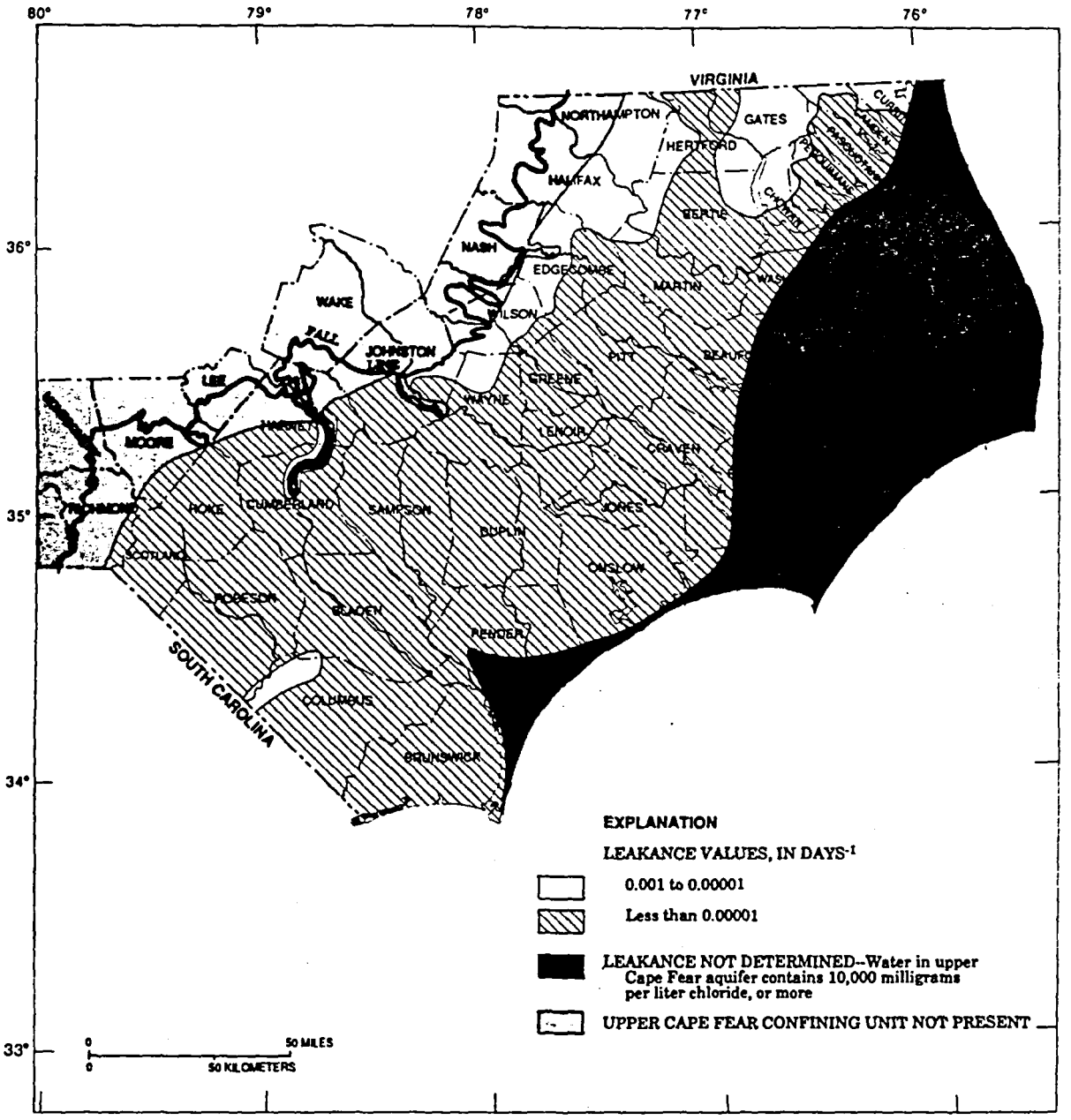


Figure 51.--Model-derived leakance (TK) of the upper Cape Fear confining unit (CU3).

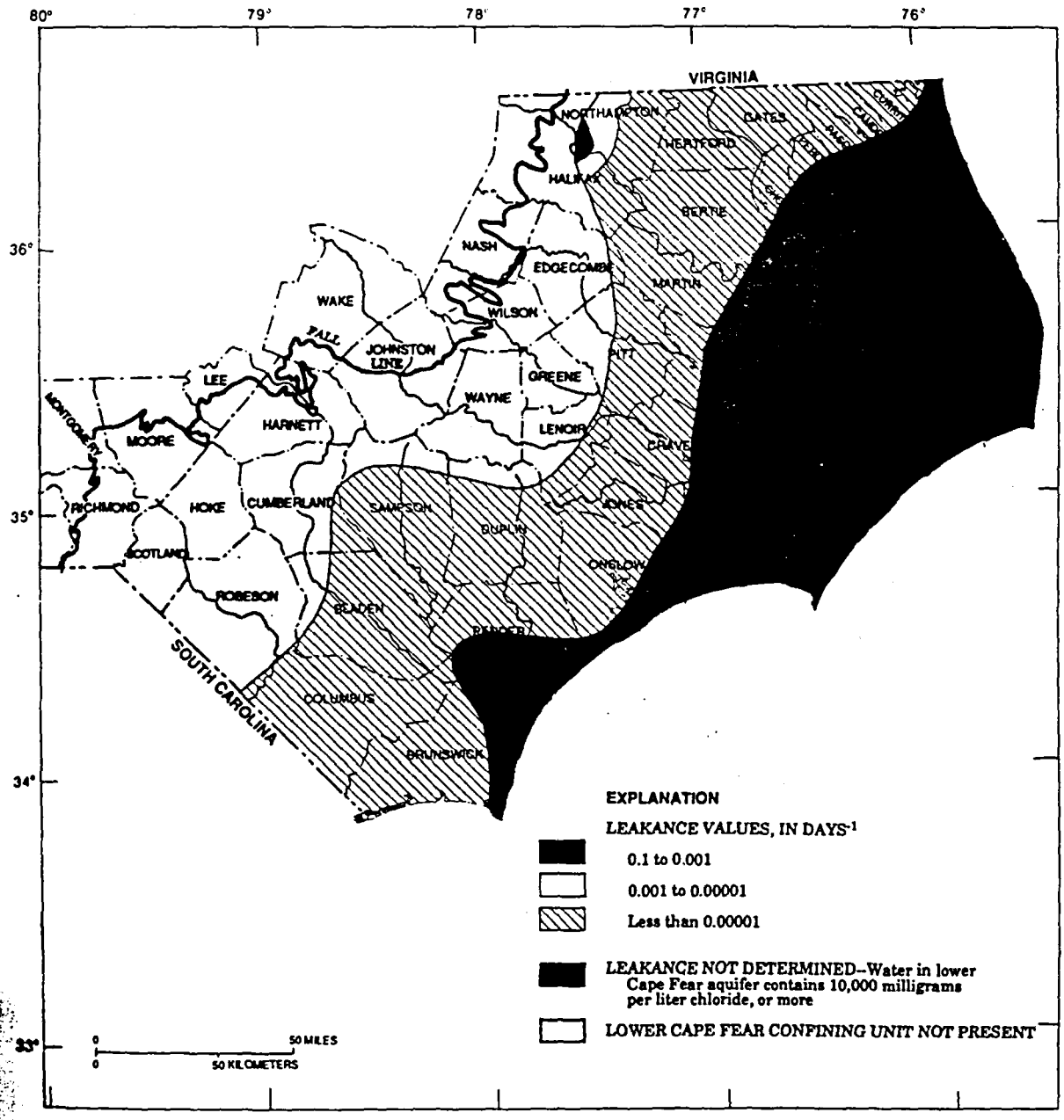


Figure 52.--Model-derived leakance (TK) of the lower Cape Fear confining unit (CU2).

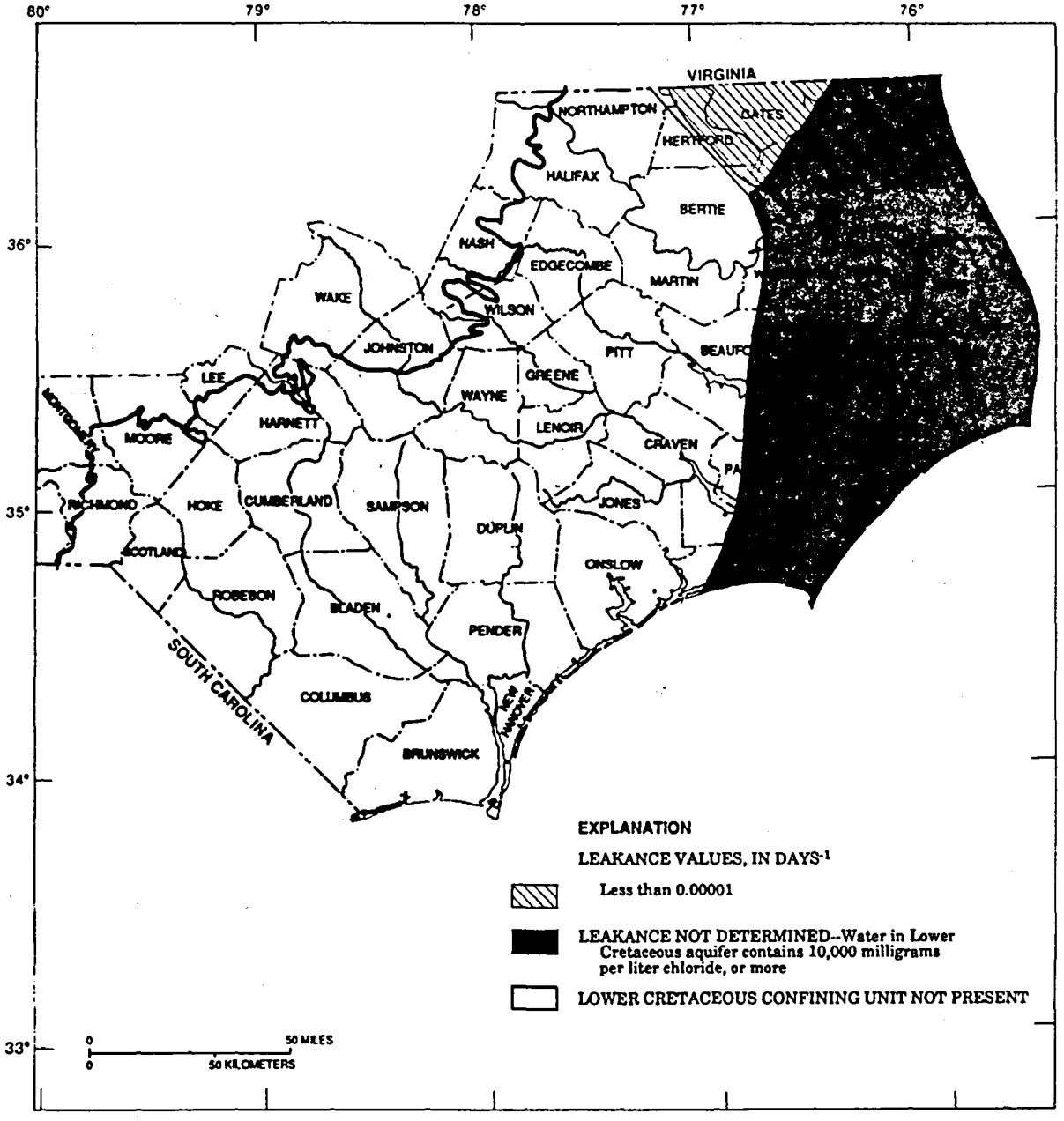


Figure 53.--Model-derived leakance (TK) of the Lower Cretaceous confining unit (CU1).

Time period	Inclusive dates	Length of time period
1	1900-1920	21 years
2	1921-1939	20 years
3	1940-1945	6 years
4	1946-1952	7 years
5	1953-1957	5 years
6	1958-1964	7 years
7	1965-1967	3 years
8	1968-1972	5 years
9	1973-1977	5 years
10	1978-1980	3 years

The locations of withdrawals greater than 100,000 gal/d are shown for all aquifers above the Lower Cretaceous aquifer (A1) in figures 55-63. (There are none in the Lower Cretaceous aquifer within North Carolina.) Table 2 shows the 1980 pumpages by aquifer.

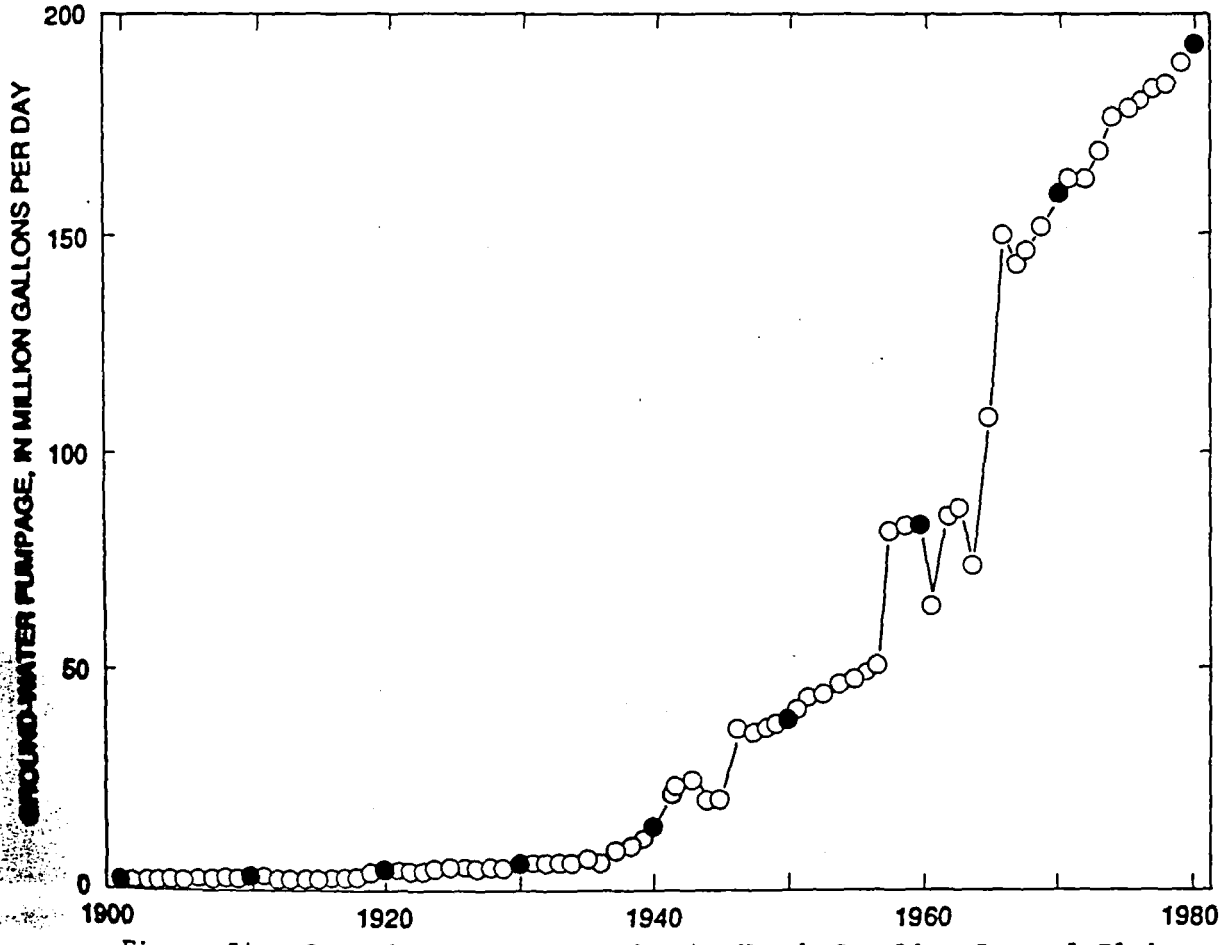


Figure 54.--Ground-water pumpage in the North Carolina Coastal Plain, 1900-80, for users of more than 100,000 gallons per day.

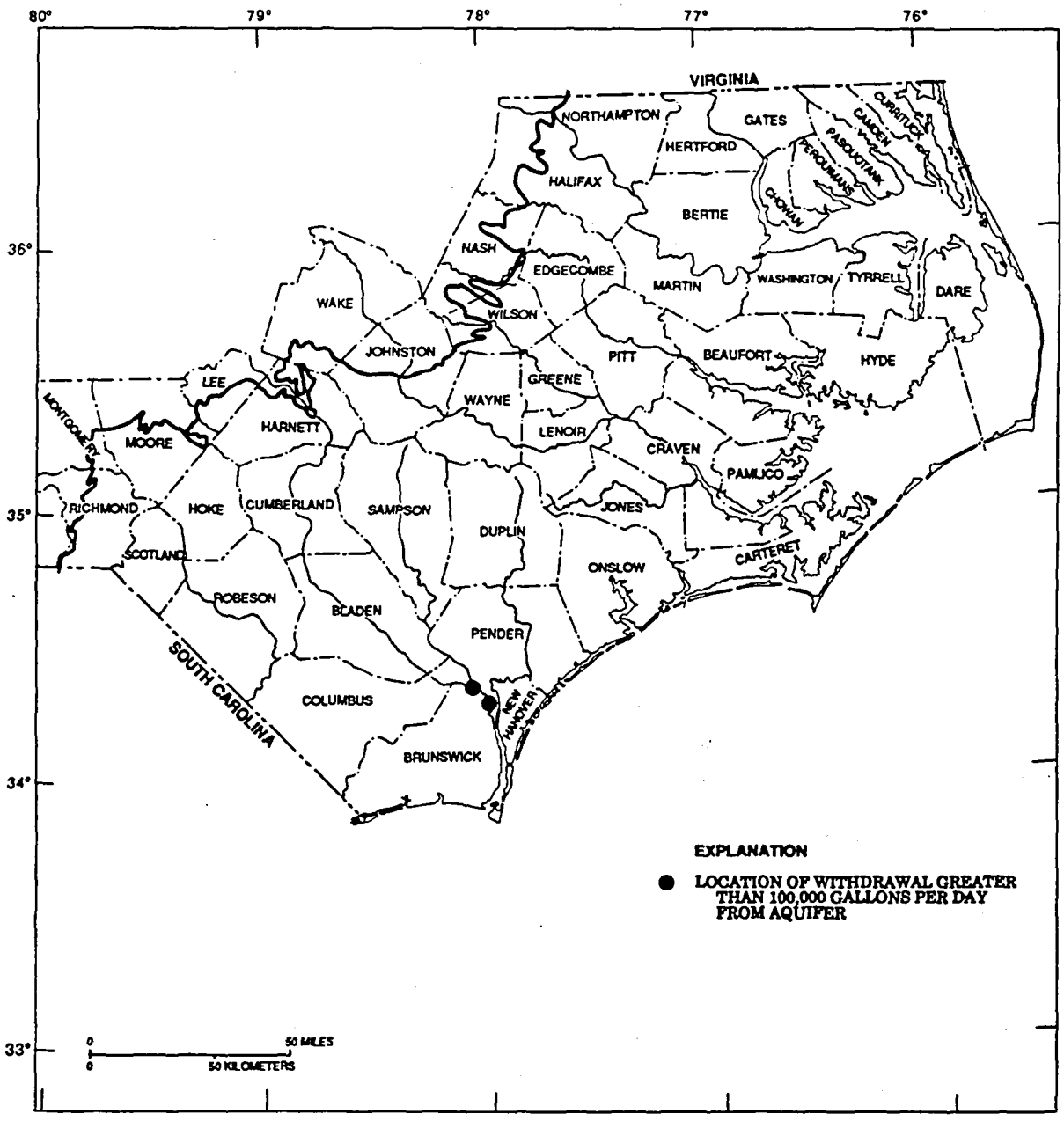


Figure 55.--Locations of withdrawals greater than 100,000 gallons per day for the surficial aquifer (A10) for 1980.

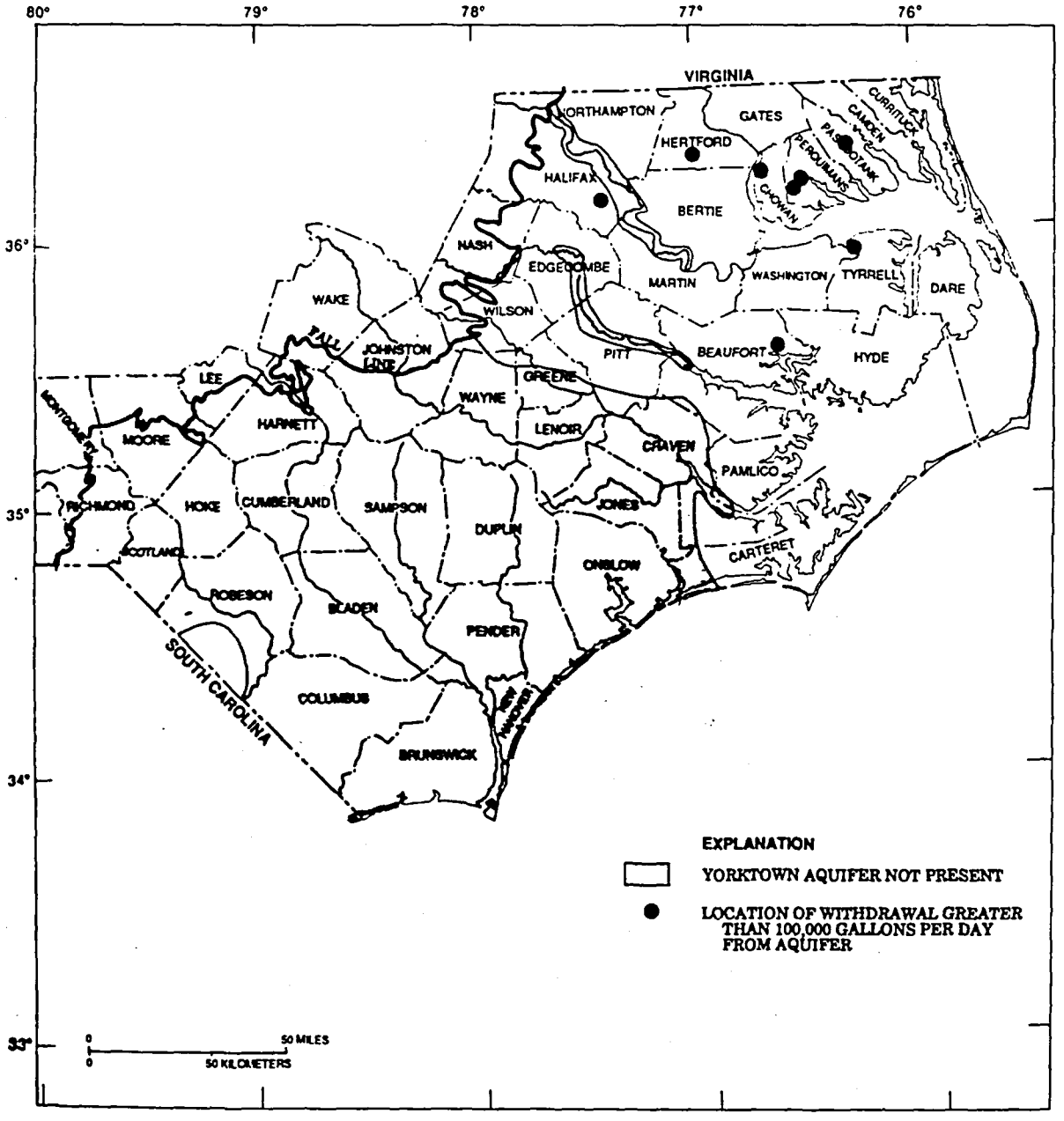


Figure 56.--Locations of withdrawals greater than 100,000 gallons per day for the Yorktown aquifer (A9) for 1980.

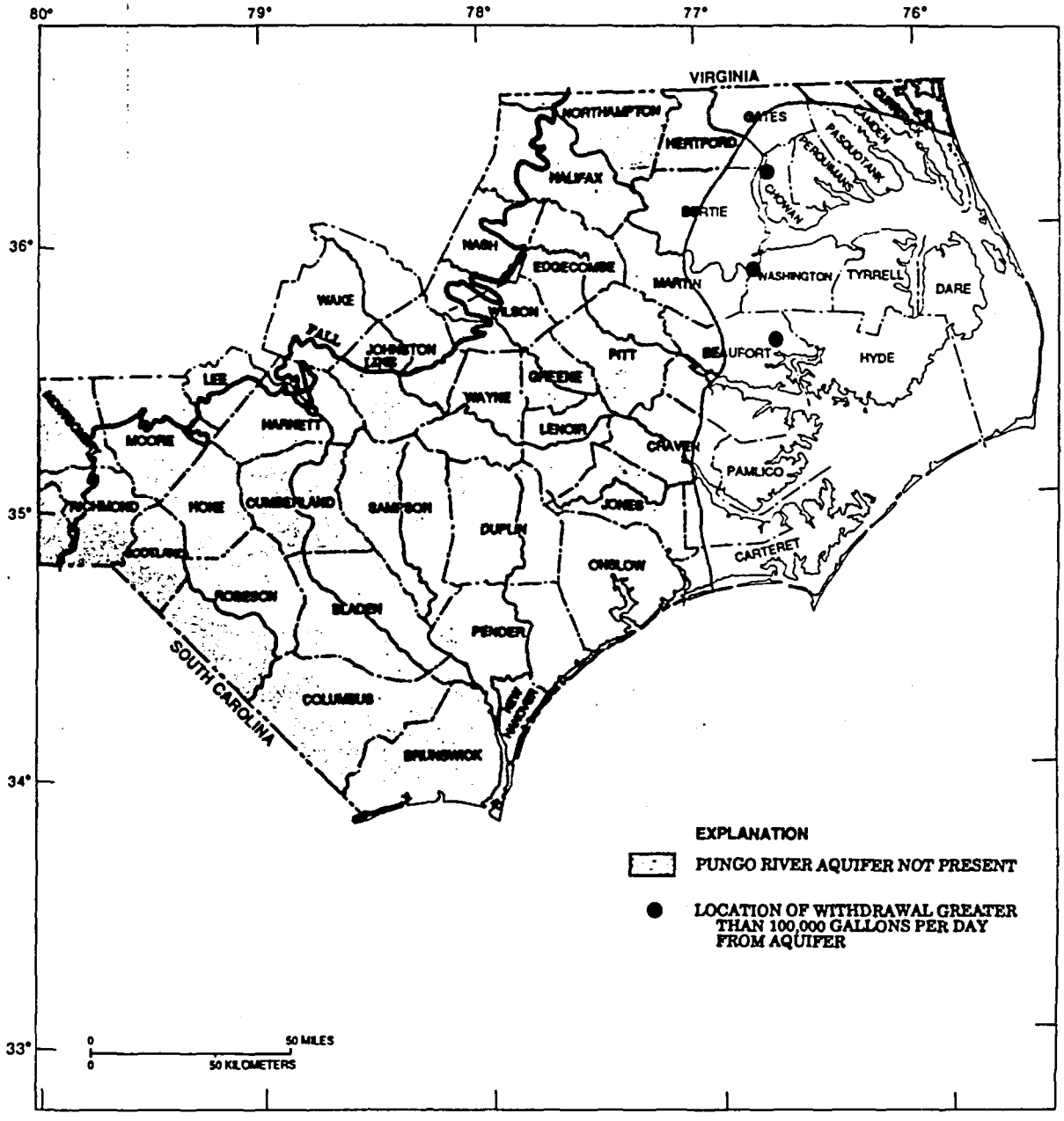


Figure 57.--Locations of withdrawals greater than 100,000 gallons per day for the Pungo River aquifer (A8) for 1980.

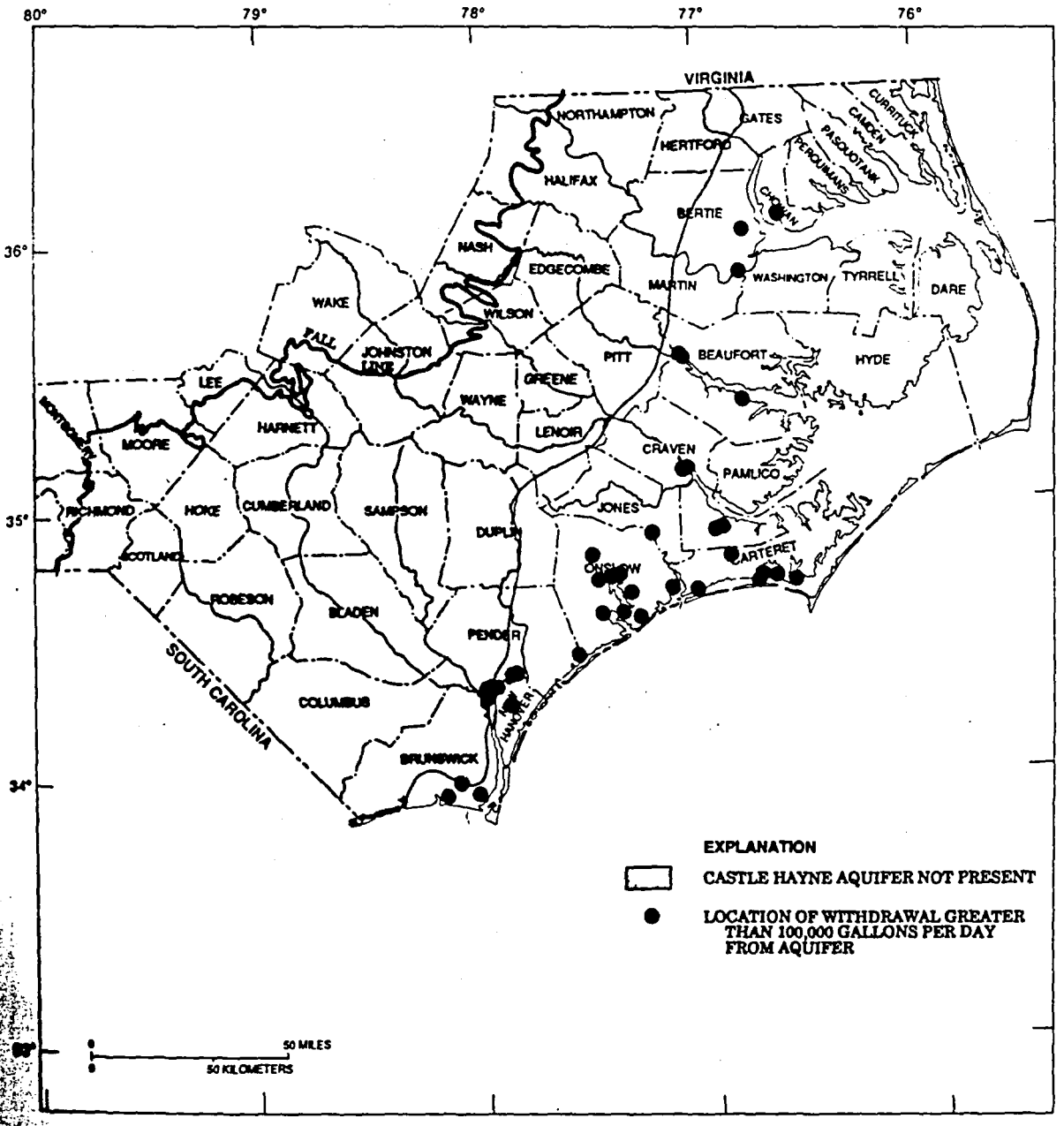


Figure 58.--Locations of withdrawals greater than 100,000 gallons per day for the Castle Hayne aquifer (A7) for 1980.

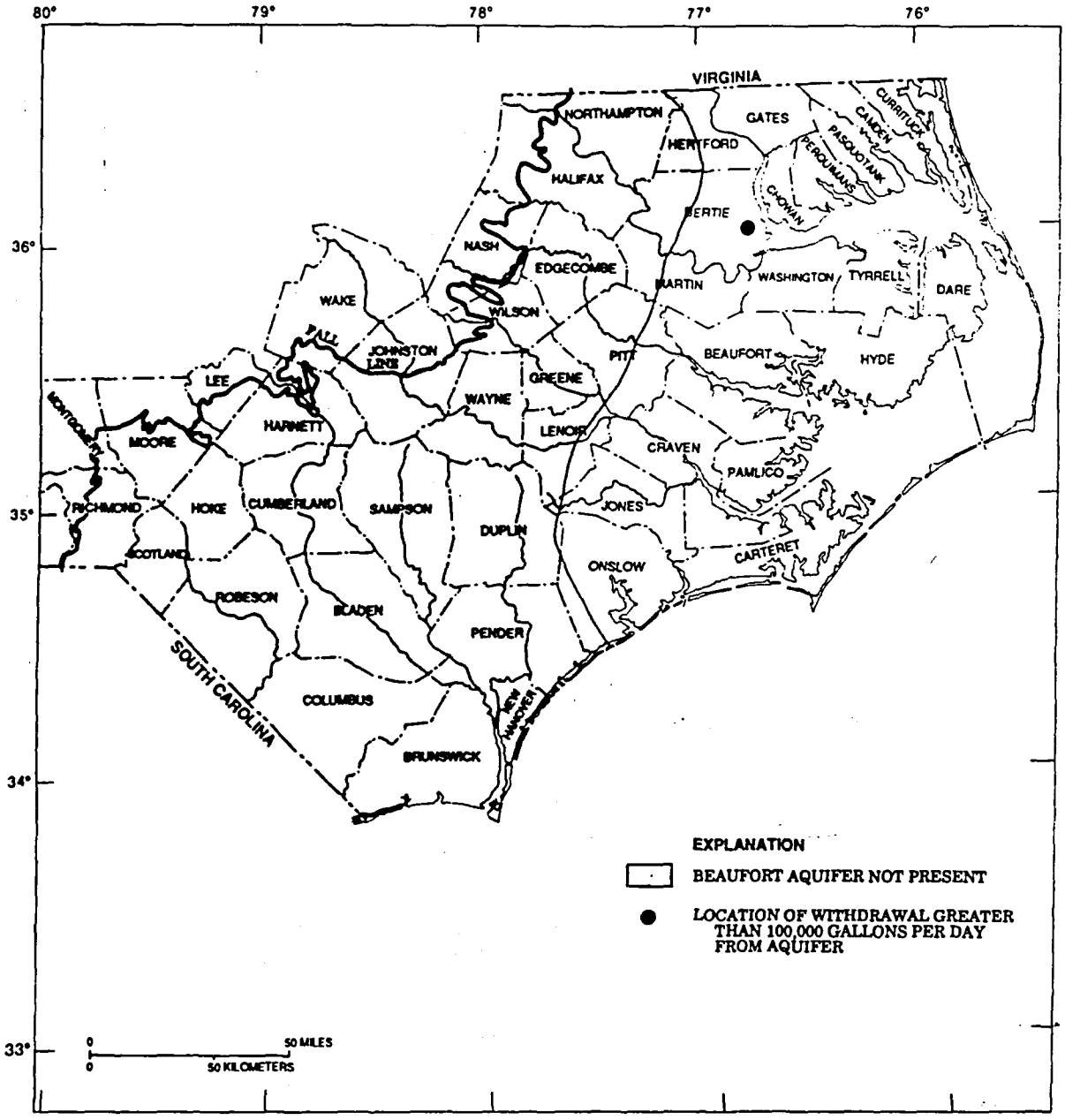


Figure 59.--Locations of withdrawals greater than 100,000 gallons per day for the Beaufort aquifer (A6) for 1980.

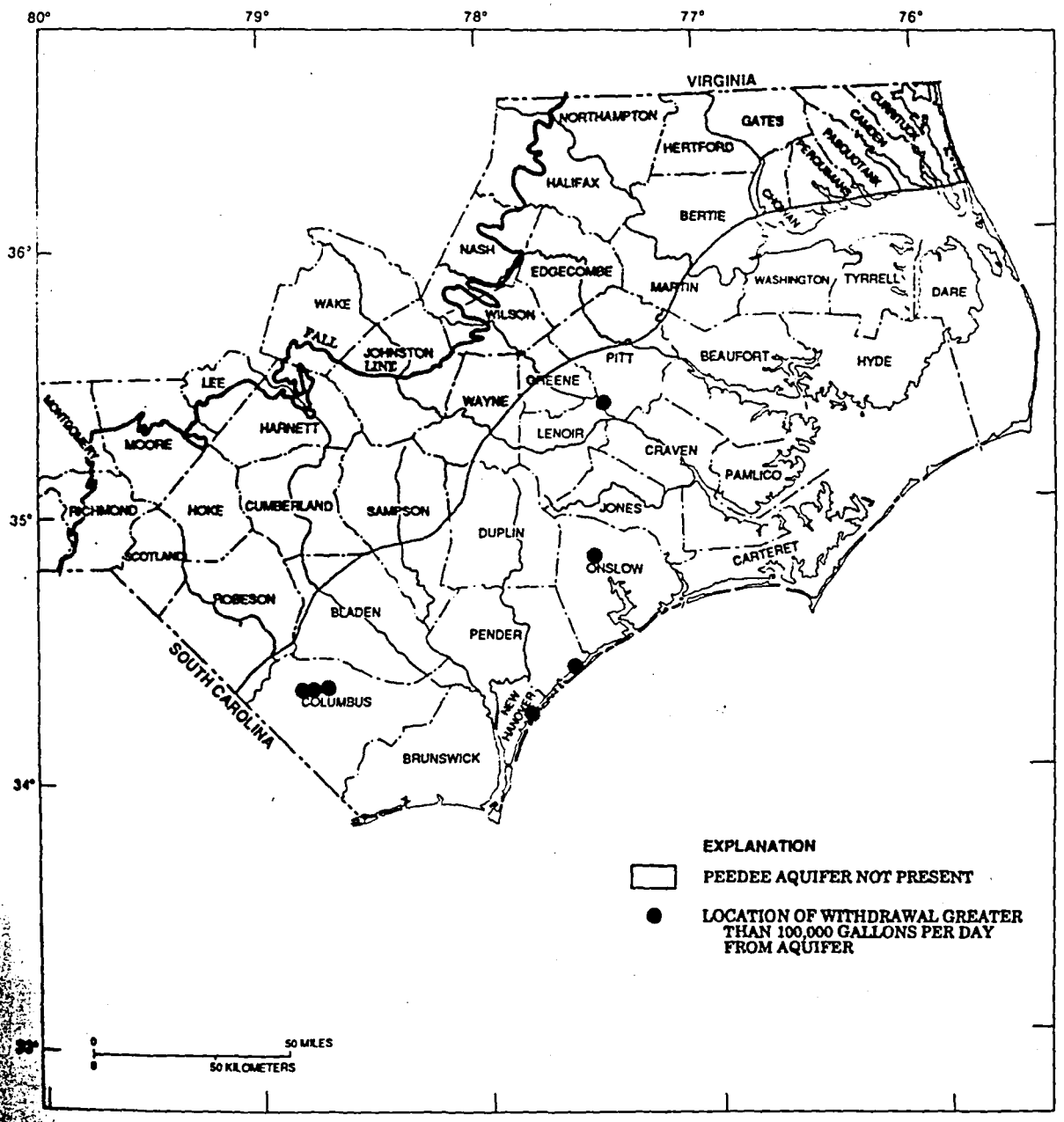


Figure 60.--Locations of withdrawals greater than 100,000 gallons per day for the Peedee aquifer (A5) for 1980.

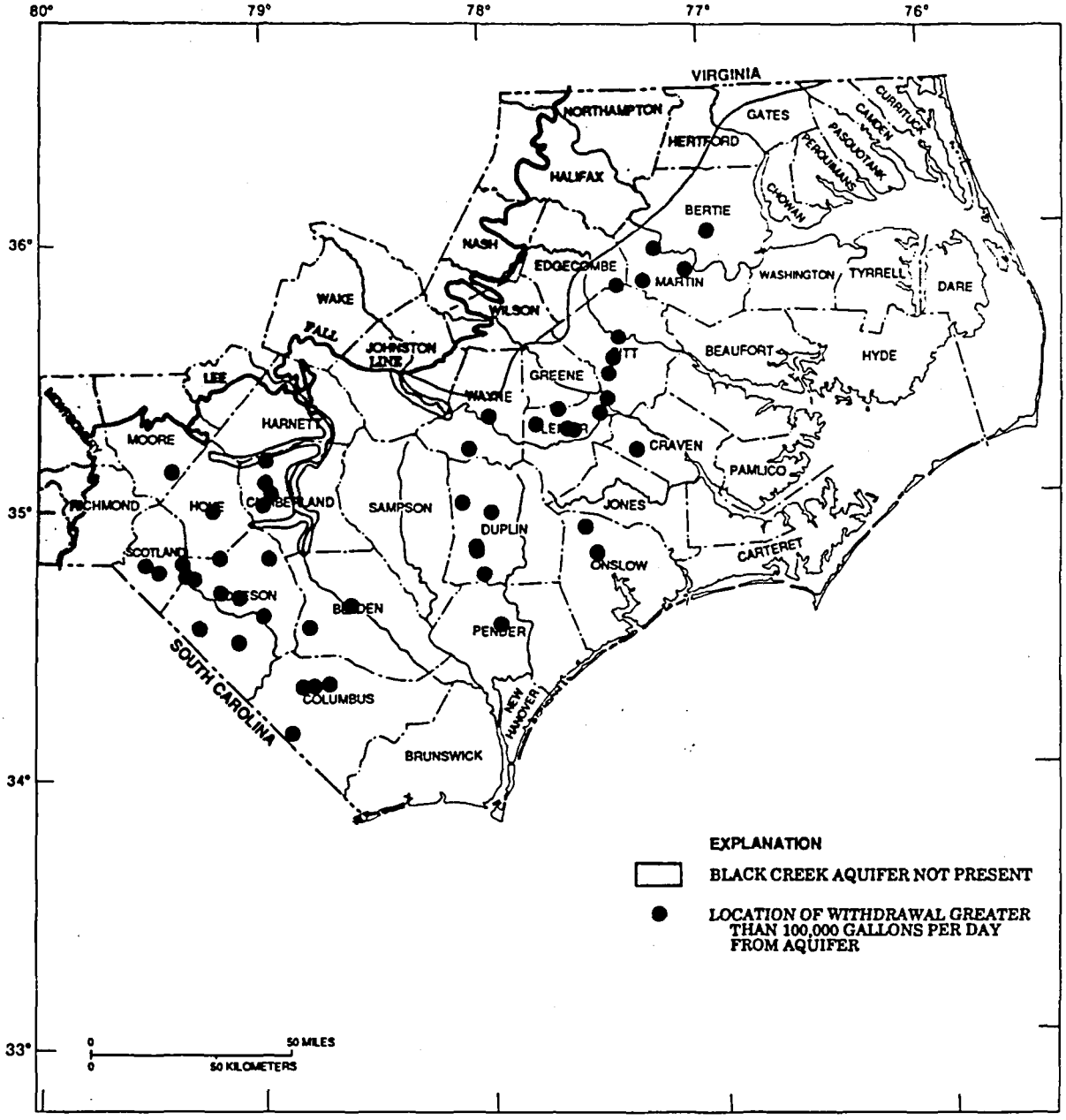


Figure 61.--Locations of withdrawals greater than 100,000 gallons per day for the Black Creek aquifer (A4) for 1980.

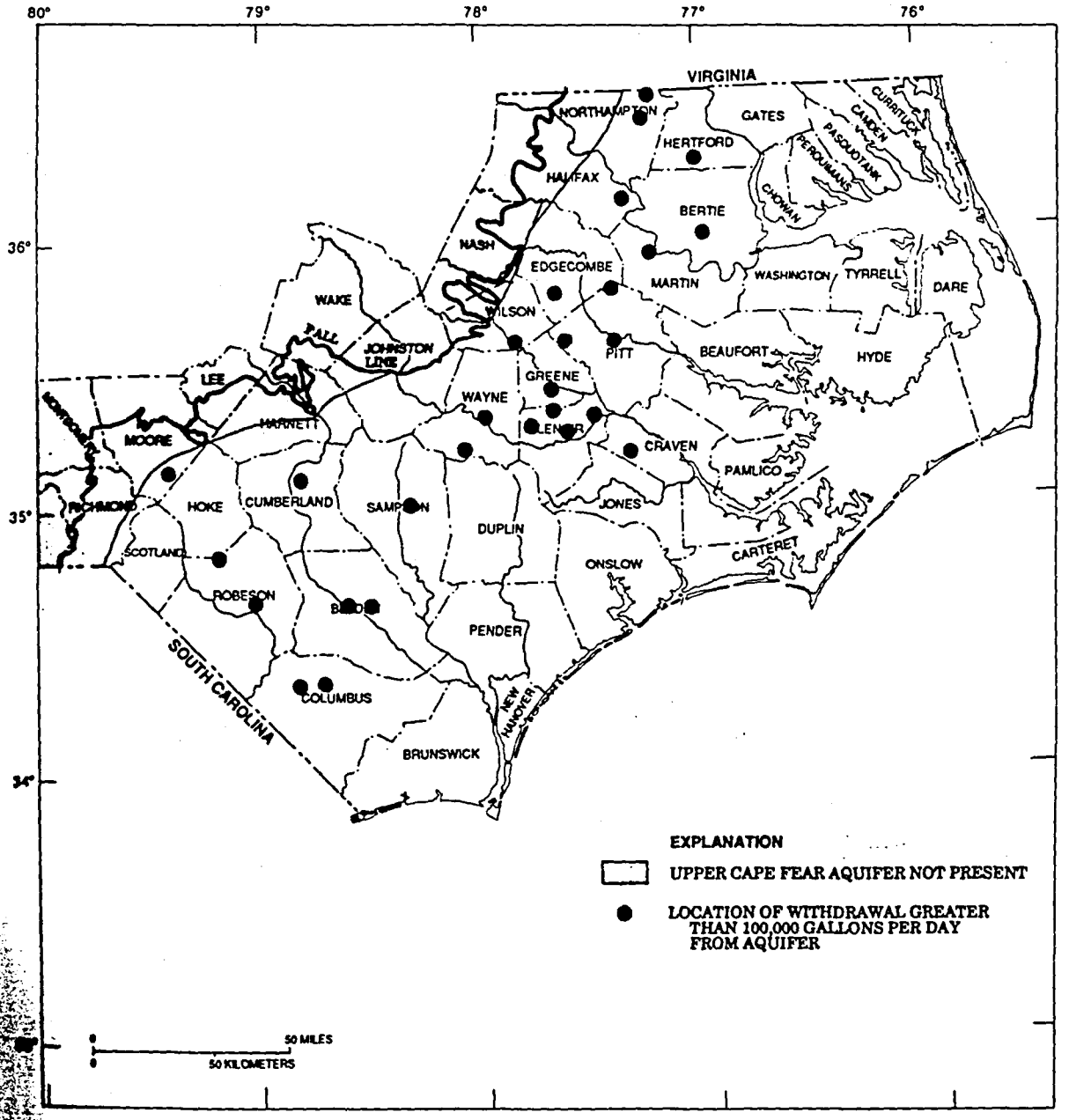


Figure 62.--Locations of withdrawals greater than 100,000 gallons per day for the upper Cape Fear aquifer (A3) for 1980.

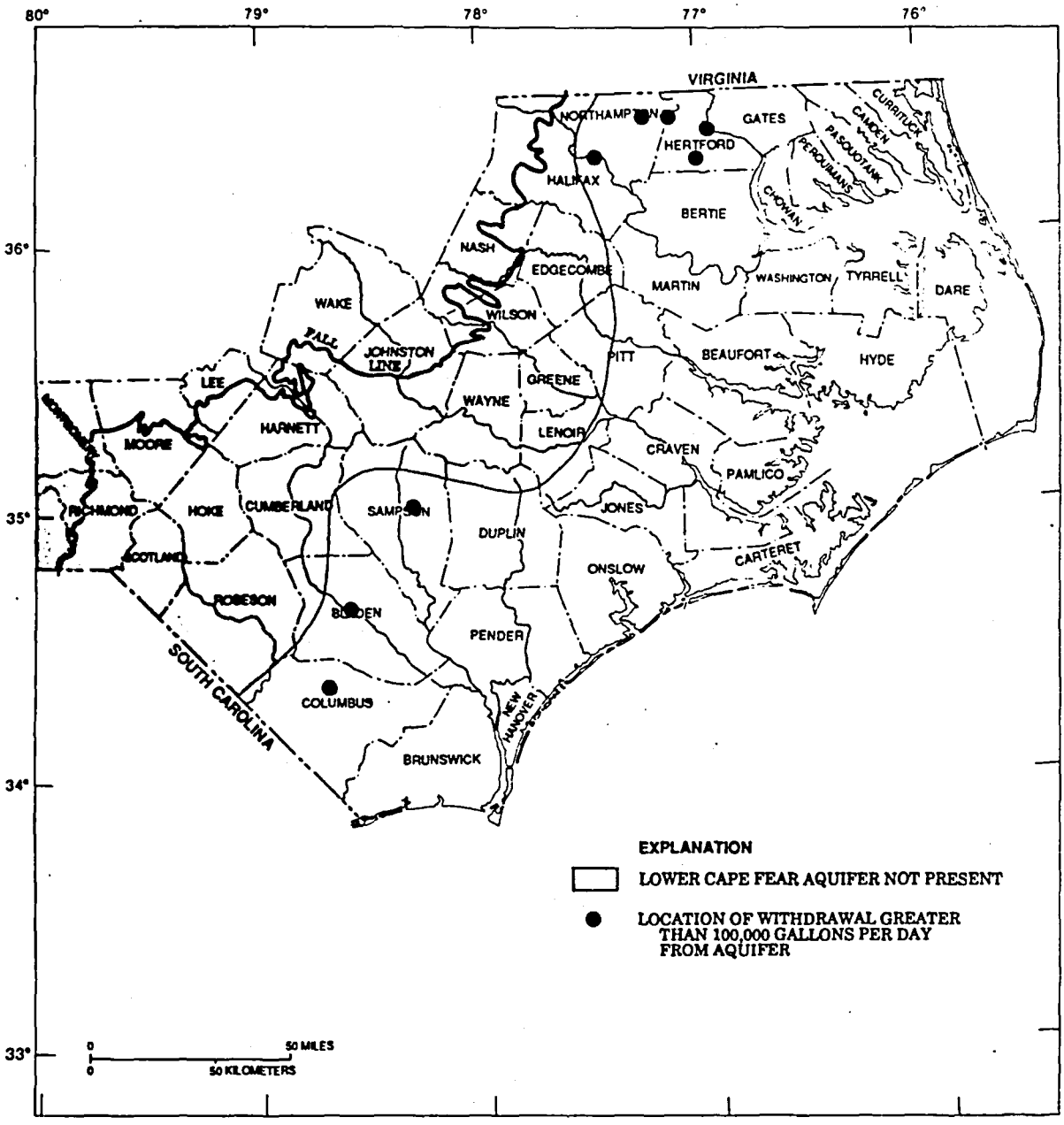


Figure 63.--Locations of withdrawals greater than 100,000 gallons per day for the lower Cape Fear aquifer (A2) for 1980.

Table 2.--*North Carolina ground-water pumpage by aquifer in 1980*

Model layer number	North Carolina aquifer names	1980 pumpage, in millions of gallons per day
A10	Surficial aquifer	0.3
A9	Yorktown aquifer	2.9
A8	Pungo River aquifer	1
A7	Castle Hayne aquifer	136
A6	Beaufort aquifer	.1
A5	Peedee aquifer	3.5
A4	Black Creek aquifer	36.6
A3	Upper Cape Fear aquifer	12.3
A2	Lower Cape Fear aquifer	2.9
A1	Lower Cretaceous aquifer	0
	Total pumpage	195.6

The pumpage survey conducted as a part of this study is considered to be fairly complete for large public and industrial ground-water users, but no irrigation water-use data was included in the survey. Ground-water used for irrigation represents a small but rapidly increasing component of total water use in the North Carolina Coastal Plain, and only one published inventory (North Carolina Department of Natural Resources and Community Development and U.S. Water Resources Council, 1983) presently exists. For calibration, wells were selected that were unaffected by irrigation pumping. In addition, much of the ground water used for irrigation purposes is withdrawn from the surficial aquifers and such withdrawals have little effect on the deeper confined aquifer system. Therefore, it is believed that the lack of irrigation pumpage data does not affect the values for transmissivity and confining-unit leakance arrived at through the calibration process.

Pumpage records prior to 1975 are incomplete and were estimated partly on the basis of population. Prior to the 1950's, many ice plants in and around the major cities of the North Carolina Coastal Plain used large amounts of ground water (1 Mgal/d or more); however, these plants have been closed since the 1950's. The effects of these and other unmeasured withdrawals on 1980 water levels are judged to be small, largely because higher recharge rates induced by these withdrawals have replaced much of the water withdrawn decades earlier.

Model Calibration

Procedures

Calibration of the North Carolina Coastal Plain ground-water flow model was a trial-and-adjustment procedure whereby model input was varied, and the resulting model output was compared to observed values. The process was repeated to minimize the difference between computed and observed values, until the computed results agree with observed values to within some acceptable degree of accuracy. Generally, calibration was considered acceptable for purposes of this study when 1980 computed water levels were within 15 ft of water levels measured in 1980.

A number of calibration simulations were made to determine how well the North Carolina Coastal Plain ground-water flow model was able to simulate actual records of water levels both in pumped and unpumped areas of the North Carolina Coastal Plain and to indicate where further adjustments to model parameters might be needed. Where calibration was judged inadequate, hydrogeologic, hydraulic head, and water-quality data were analyzed to determine the cause or causes. Often, poor initial estimates of model parameters were suspected of being the primary cause of poor water-level matches. Adjustments of the model parameters were made and new simulations performed. Again, computed water levels were compared with observed values. Thus, an adjustment process involving several repetitions was employed in model calibration. The parameter most often adjusted was leakance of confining units (TK), followed by transmissivity of the aquifers (T). The other major hydraulic property represented in the model, storage coefficient (S), was not varied during the calibration process because the model was found not to be sensitive to changes in the values of the storage coefficient. Other model variables that were varied during the course of model calibration were the altitude of the water table, model-boundary fluxes, location of freshwater-saltwater boundaries, and pumping rates.

Large changes in leakance values from initial estimates (an order of magnitude or more) were considered justified because the vertical conductivity of confining units is not well known. However, changes in transmissivity were limited to no more than three times as much or no less than one-third as much as initial estimates because probable errors in initial estimates were much smaller than probable errors in estimates of leakance.

As a result of sensitivity analyses performed early in model calibration, it was found that changing transmissivity values produced large changes in computed heads near pumping centers, but away from pumping centers changes were small; changes in leakance of confining units also produced large changes in computed heads near pumping centers, but the changes away from pumping centers were often significant, too. If the computed water levels were too high or too low very near the pumping centers, but not elsewhere, a transmissivity problem was suspected. If computed water levels were found to be generally too high or too low in a given layer over a large area, a leakance problem was suspected. The vertical flow system was then examined to estimate what changes in model parameters would be most likely to result in better water-level matches, not only in the layer in question, but also in the underlying and overlying layers.

In selecting wells with water-level records for calibration purposes, areas which have experienced water-level declines very close to freshwater-saltwater boundaries (10,000 mg/L chloride concentration) were avoided. One model assumption is that the freshwater-saltwater boundary is a no-flow boundary. This assumption is not valid in areas where pumping may have induced flow of saltwater toward the pumping well, and it was felt that attempts to match hydrographs in such areas would be unrealistic. Full consideration of movement of saltwater requires a ground-water flow model capable of simulating waters of varying density and is beyond the scope of this study.

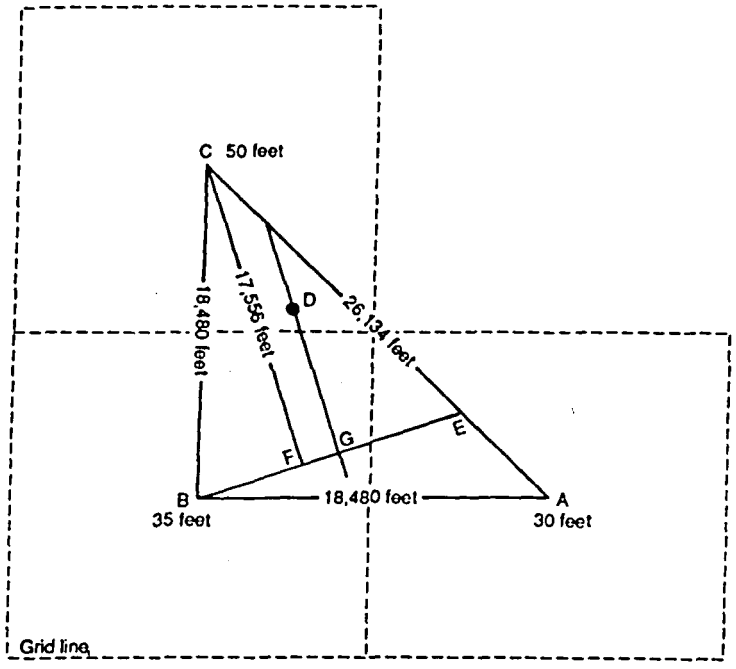
The assumption of no flow across the freshwater-saltwater boundaries is of particular concern in parts of aquifers A1 through A4 and part of A6, where simulated drawdowns near the freshwater-saltwater boundary commonly exceeded 10 ft in 1980. In these areas, actual drawdowns would likely be less than those simulated by the model. As a result, the confidence in model results (calibrated parameters) and predictions are less in these areas. The reader is referred to Leahy and Martin (in press) for a detailed discussion of the effect of the no-flow assumption for the freshwater-saltwater boundaries on the results of the regional ground-water flow model of the northern Atlantic Coastal Plain.

When testing model parameters during the course of model calibration, the usual procedure was to make three simulations. The first simulation was for steady-state prepumping conditions with water-table heads fixed at constant values indicative of average long-term natural conditions. Boundary fluxes were provided by the regional model, which was frequently updated with refined flux values derived from each State subregional model.

Model output from this first simulation included flux between the water table and the topmost confined aquifer. This flux can be thought of as the deep percolation (DP) term of equation (3), which is the total ground-water recharge (QRE) minus base flow of streams (BF).

The quantity QRE for each node was determined as described earlier in the "Model Input" section of the report. Subtracting or adding DP to this value (depending on the direction of vertical flow) gave BF for each node. Knowing also the altitude of the water table, h_a, and the lowest stream altitude in each node, h_s, equation 2 could be solved for streambed leakance (SL). An eleventh (artificial) layer representing streams was then added to the model. The head at each stream node was set at the constant head, h_s, and the calculated value of SL was used as the TK value for use between the stream layer and the water-table layer. Recharge (QRE) was added to the surficial aquifer (A10) and a steady-state nonpumping simulation was made. The advantage of adding a layer representing streams is that, in later stressed simulations, the water levels are free to fluctuate within the surficial aquifer due to stresses either in it or in underlying aquifers. This results in a more realistic simulation of the surficial aquifer response to pumping stresses than in simulations where the water table is held constant.

A pumping simulation was then made, designed to simulate aquifer response to pumpage over the 10 pumping periods discussed earlier in the section "Ground-Water Withdrawals and Time Discretization." Simulated hydrographs were compared to observed hydrographs for both prepumping and pumping conditions. A significant feature of the simulated hydrographs is that discretization error was reduced by computing heads at well locations, most of which are not at grid centers. This method of head computation involves solution of the common three-point problem as shown in figure 64.



EXPLANATION

1. Locate three computed heads (h) at grid nodes that form a triangle **ABC** enclosing an off-node point of interest **D**.
2. Find the direction of ground-water flow and hydraulic gradient in the plane defined by the apexes of the triangle:

   - Locate the triangle apex that has the intermediate water level **B**.
   - By linear interpolation, find the point on the side opposite **E** that has the same water level as **B**.
   - Draw line **BE**. This is a line of equal water level, 35 ft (feet) in this case.
   - Draw a line perpendicular to the equal water-level line **BE** that passes through either the the apex of the higher or lower water levels. The resulting line **CF** represents the direction of the hydraulic gradient. Calculation of the gradient is as follows:

$$\frac{h_C - h_E}{\text{distance CF}}, \text{ or } \frac{50 - 35 \text{ ft}}{17{,}556 \text{ ft}} = 0.00085 \text{ foot per foot.}$$

3. Draw a line parallel to the direction of the gradient that passes through the point **D** at which the head is to be computed.
4. Measure distance from a point of known head **G** to point at which head is to be calculated (line **DG**).
5. Knowing the hydraulic gradient (0.00085 foot per foot), the head at point **G** (35 ft), and the distance along flow path at **DG** (8,316 ft), the head at point **D** (h_D) may be calculated:

$$\frac{h_D - 35 \text{ ft}}{8{,}316 \text{ ft}} = 0.00085; \; h_D = 42.07 \text{ ft.}$$

Figure 64.--Diagram showing method of computing heads at off-node locations.

Results

As previously mentioned, leakance (TK) of confining units was adjusted more often and to a greater degree than any other model parameter. Computed heads were found to be significantly sensitive to changes in this parameter. At the same time, large leakance adjustments of as much as two orders of magnitude could be justified in many instances because estimated initial values of this parameter were subject to more uncertainty than any other model parameter. Part of this uncertainty has to do with the difficulty in distinguishing silt from clay on geophysical logs, and part has to do with the discontinuity of some confining units which often cannot be estimated from interpolation between geophysical logs collected at widely-spaced locations.

Trial and adjustment model calibration indicated a general tendency for vertical hydraulic conductivity of confining units, K_v, to decrease with increasing depth and with increasing distance downdip. The tendency for the decrease with depth is reflected by minimum K_v values in table 3 and is thought to be partly related to greater compaction of the silts and clays due to the greater weight of overlying sediments and the greater time for compaction. The tendency for decreasing K_v with increasing distance downdip follows from this because, downdip, sediments of a given aquifer are generally more deeply buried; and there may also be a general downdip change from coarse clastic to fine clastic to marine facies (LeGrand, 1961). A countertendency to this decrease of K_v with increasing depth and distance downdip may occur where nonmarine sediments are present, such as in large parts of the lowermost confining units CU1, CU2, and CU3. There, beds comprising the confining units are more likely to be discontinuous and, therefore, provide less resistance to vertical movement of water than suggested from the thickness of confining-unit material indicated on geophysical logs. Hence model values of K_v may be higher there (and elsewhere) than might be expected for silt or clay in order to reflect discontinuities.

Transmissivity (T) was varied less often than leakance during model calibration. Initial estimates of T were changed for three aquifers during the course of model calibration--the Castle Hayne aquifer (A7), the Black

Creek aquifer (A4), and the upper Cape Fear aquifer (A3). Initial values of transmissivity for the Castle Hayne aquifer in Beaufort County, which were estimated from geophysical logs, gave computed heads which were tens of feet lower than observed heads. When transmissivity values were increased by a factor of 2.5 in that area, matches were much closer and were in better agreement with aquifer tests reported by DeWiest and others (1967). No attempt was made to calibrate for transmissivity values in the surficial aquifer (A10).

Table 3.--*Ranges of vertical hydraulic conductivity (K_v) of confining units for the calibrated model*

Model layer number	Vertical hydraulic conductivity of confining units (K_v), in feet per day	
	Maximum values	Minimum values
9	6.98×10^{-3}	6.82×10^{-3}
8	7.94×10^{-3}	3.90×10^{-3}
7	9.07×10^{-4}	3.01×10^{-4}
6	5.88×10^{-4}	1.46×10^{-4}
5	3.89×10^{-4}	7.71×10^{-5}
4	2.77×10^{-4}	3.42×10^{-5}
3	2.52	6.84×10^{-6}
2	4.96×10^{-1}	4.13×10^{-6}
1	2.88×10^{-4}	4.04×10^{-5}

For the block representing the Castle Hayne aquifer (A7) at Lee Creek (row 28, column 37), modeled transmissivity was 41,200 ft^2/d for an aquifer thickness of about 340 ft (inferred horizontal hydraulic conductivity is about 121 ft/d). Values derived by DeWiest and others (1967, p. 94) from aquifer-test data indicate a higher transmissivity near Lee Creek of 52,100

ft^2/d for an assumed formation thickness of 300 ft (inferred hydraulic conductivity of 174 ft/d). A limitation of the test reported by DeWiest and others (1967) is that the pumped well used in the test was open only to the top 44 ft of the Castle Hayne aquifer. Such a test may not yield hydraulic conductivities representative of the entire aquifer thickness. Thus, the lesser hydraulic conductivity calibrated for the Castle Hayne aquifer near Lee Creek is not unreasonably low compared to values reported by DeWiest and others. Also, the model-derived Castle Hayne aquifer (A7) transmissivity value at Lee Creek is very close to that derived by Sherwani for the Lee Creek area (40,100 ft^2/d) for use in his digital model (Sherwani, 1973, p. 58).

A 50-percent reduction in T from initial estimates everywhere in both the Black Creek aquifer (A4) and the upper Cape Fear aquifer (A3) resulted in generally better matches of computed heads with observed water levels. Apparently, silty clays interbedded with coarse sands in the deeply buried nonmarine and marginal-marine sediments of these aquifers were more effective in reducing the horizontal hydraulic conductivity, k_h, of the aquifer material than was first thought from examination of the geophysical logs (M.D. Winner, Jr., personal commun., September 1985). Thus, initial estimates of k_h were higher than final calibrated values.

A layer-by-layer summary of differences between observed and computed water levels for December 31, 1980, is given in table 4. The average difference between computed and observed water levels for 191 water-level observation wells was slightly less than +1.6 ft. Detailed comparisons of computed and observed values over time were also made. Nearly 240 computed hydrographs were compared with observed hydrographs. Figures 65-69 show selected hydrograph comparisons made during the course of model calibration. Those shown were chosen on the basis of length of record and a balanced geographic and aquifer distribution.

A number of poor matches of computed and observed water levels were attributed to discretization scale rather than to poor estimates of hydrologic parameters. For example, drawdowns due to pumpage are treated by the model as if water levels are drawn down evenly over an entire block,

rather than as a cone of depression around a pumped well, and the three-point method illustrated in figure 64 does not completely correct for this where grid size is large. The coarse model grid makes errors from this source significant, particularly when computed values for a node are compared to values for an observation well located very close to a pumping well.

Table 4.--*Summary of differences between computed and observed water levels for December 31, 1980*

Aquifer names	Model layer number	Average difference in water levels, in feet. Values represent computed minus observed differences.					
		All differences		Positive (+) differences only		Negative (-) differences only	
		Number of values	Average difference	Number of values	Average difference	Number of values	Average difference
Yorktown	A9	27	+1.4	16	+4.5	11	-3.4
Pungo River	A8	3	+4.2	3	+4.2	0	-
Castle Hayne	A7	47	+2.4	32	+7.3	15	-7.8
Beaufort	A6	5	+2.7	4	+5.2	1	-7.2
Peedee	A5	28	+0.2	12	+11.2	16	-8.1
Black Creek	A4	34	-1.0	14	+15.1	20	-12.4
Upper Cape Fear	A3	30	+7.3	21	+13.5	9	-7.3
Lower Cape Fear	A2	16	-5.0	5	+12.3	11	-12.9
Lower Cretaceous	A1	1	+14.8	1	+14.8	0	--

The scale of discretization is probably also responsible for several poor hydrograph matches in the Sand Hills area (fig. 1). Topographic relief and water-table gradients are greater in the Sand Hills region than in any other part of the North Carolina Coastal Plain, but the model grid is not fine enough to adequately reflect this variation. Thus, matches of computed with observed water levels were generally poor in this area, and the degree to which the model can be considered calibrated is much less for the Sand Hills region than for other parts of the North Carolina Coastal Plain. One practical consequence of this situation is that the accuracy of estimates of model parameters given by the flow model for the Sand Hills area is more uncertain than elsewhere. Future ground-water modeling studies of the Sand Hills region could obtain better results by utilizing a much finer model grid than that used in this study.

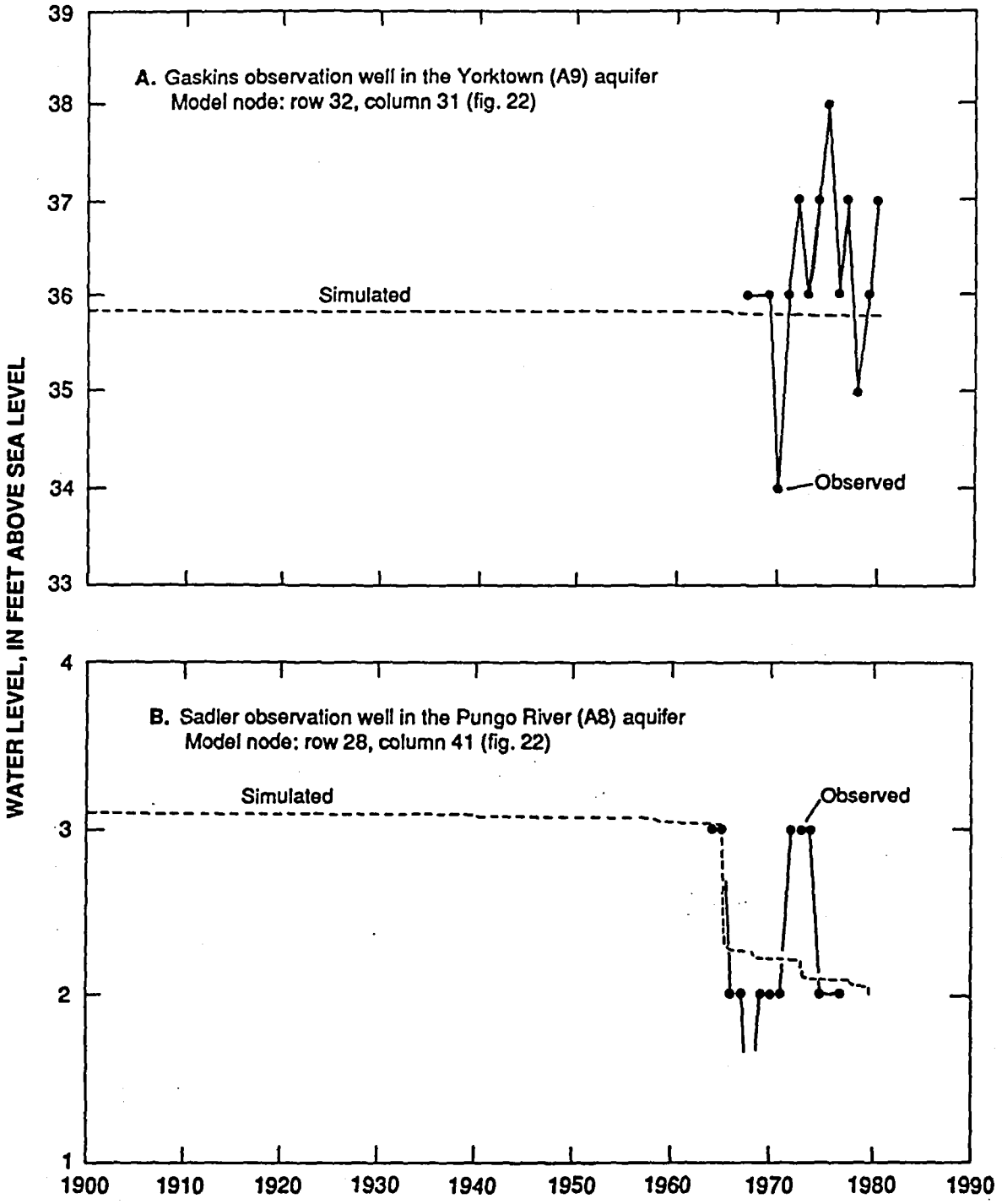


Figure 65.--Observed and simulated water levels in (A) the Yorktown and (B) the Pungo River aquifers.

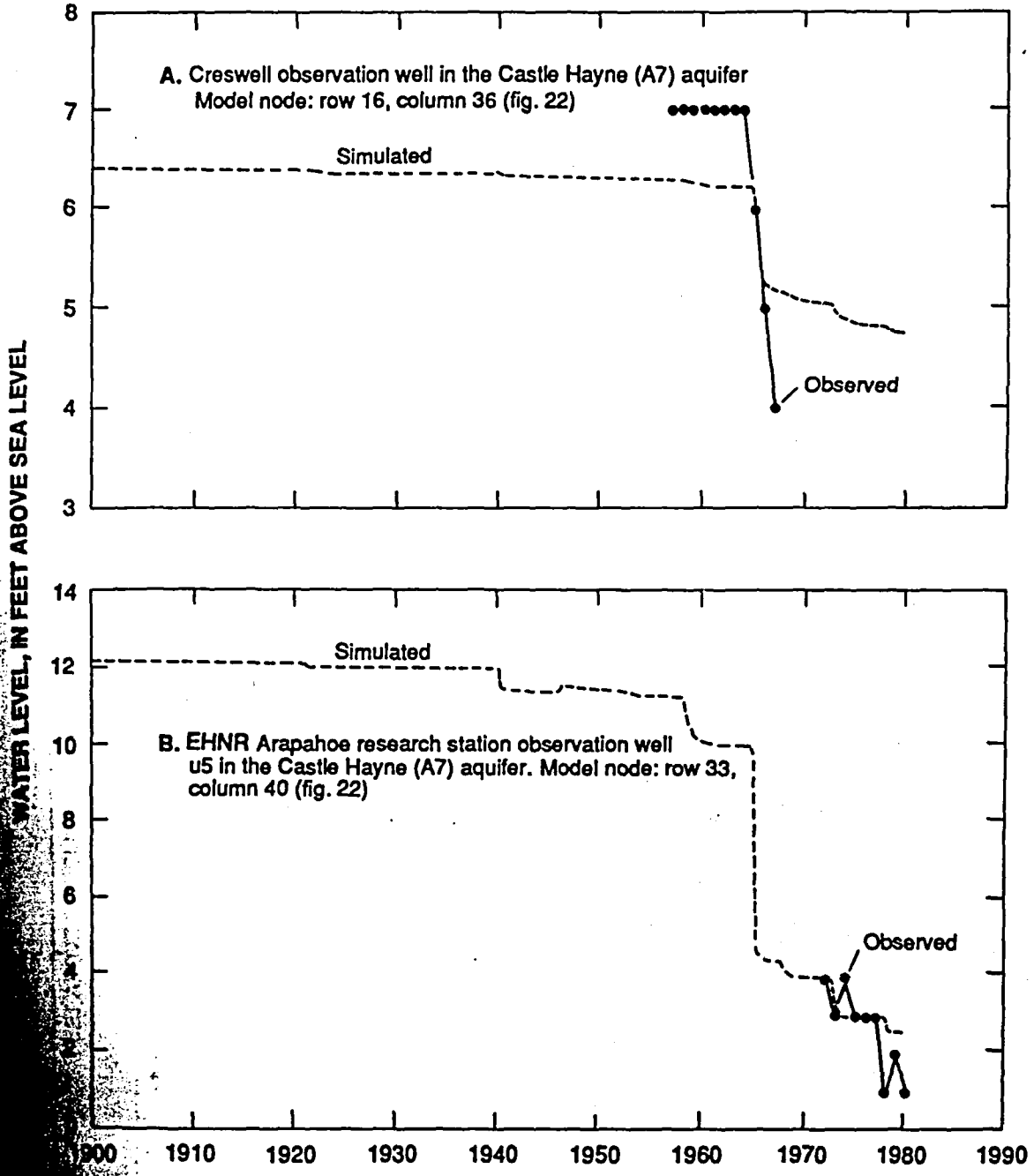


Figure 66.--Observed and simulated water levels in the Castle Hayne aquifer at (A) the Creswell observation well and (B) EHNR Arapahoe research station well u5.

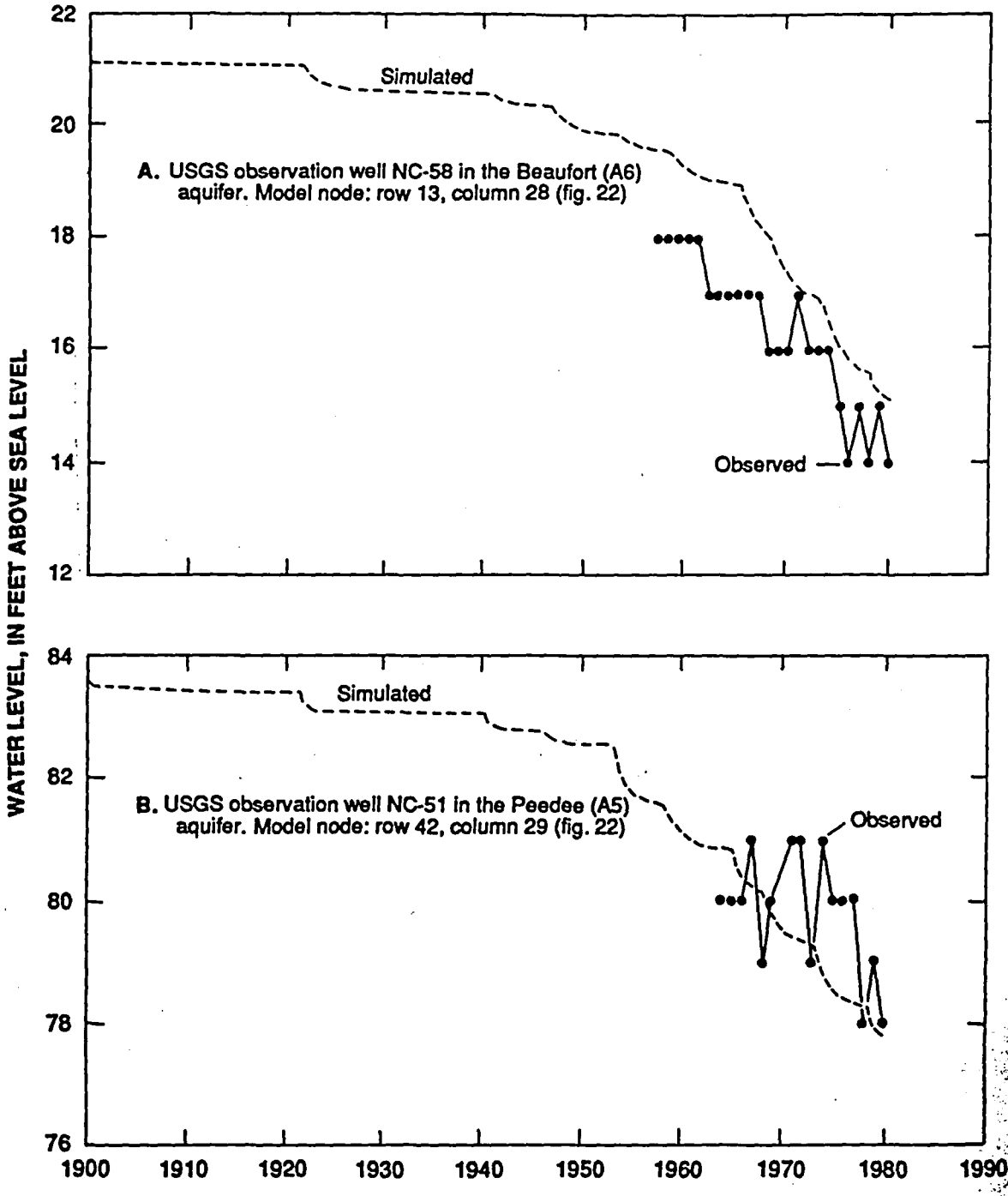
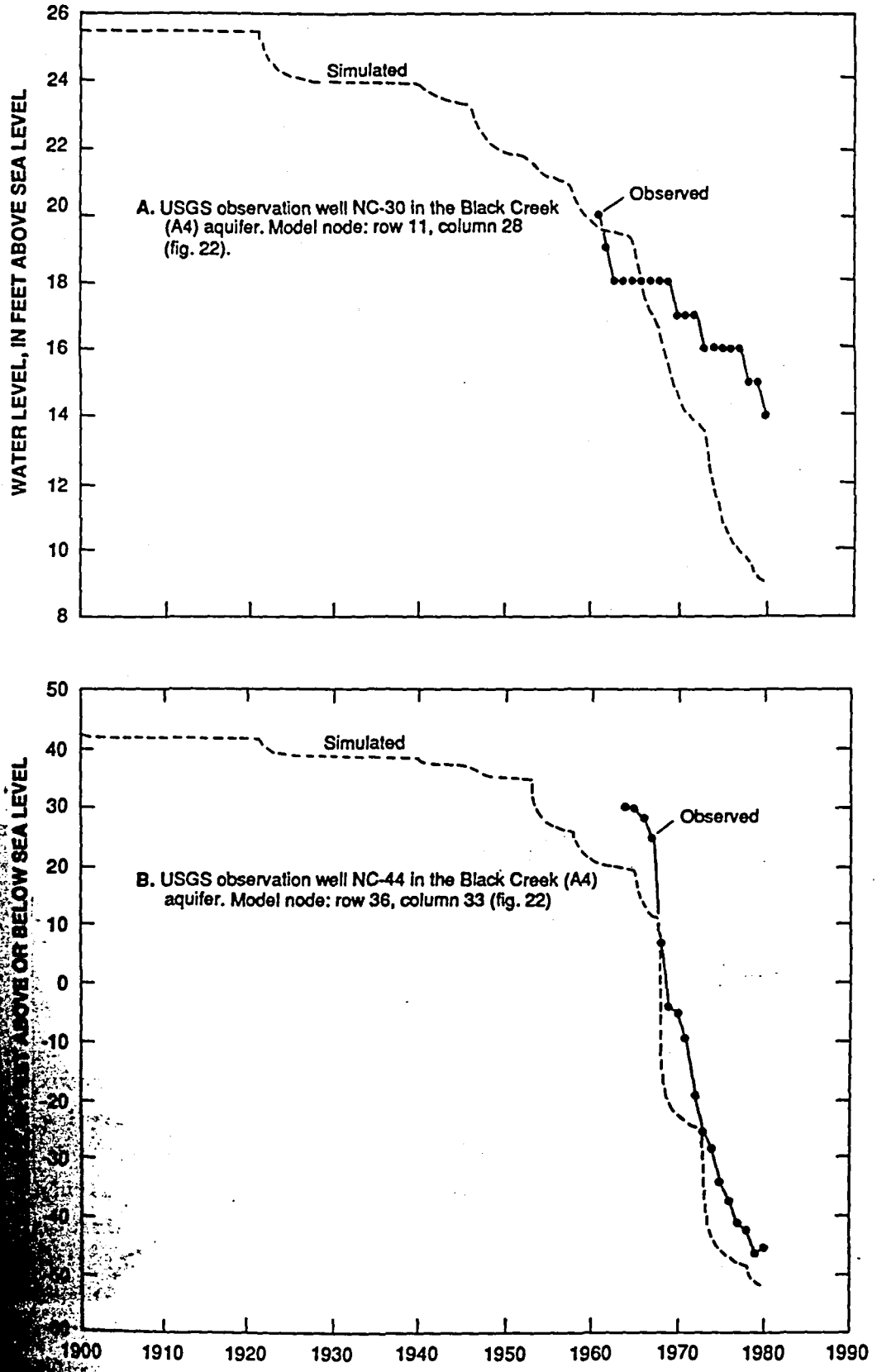


Figure 67.--Observed and simulated water levels in the (A) Beaufort and (B) Peedee aquifers.



58.--Observed and simulated water levels in the Black Creek aquifer at USGS observation wells (A) NC-30 and (B) NC-44.

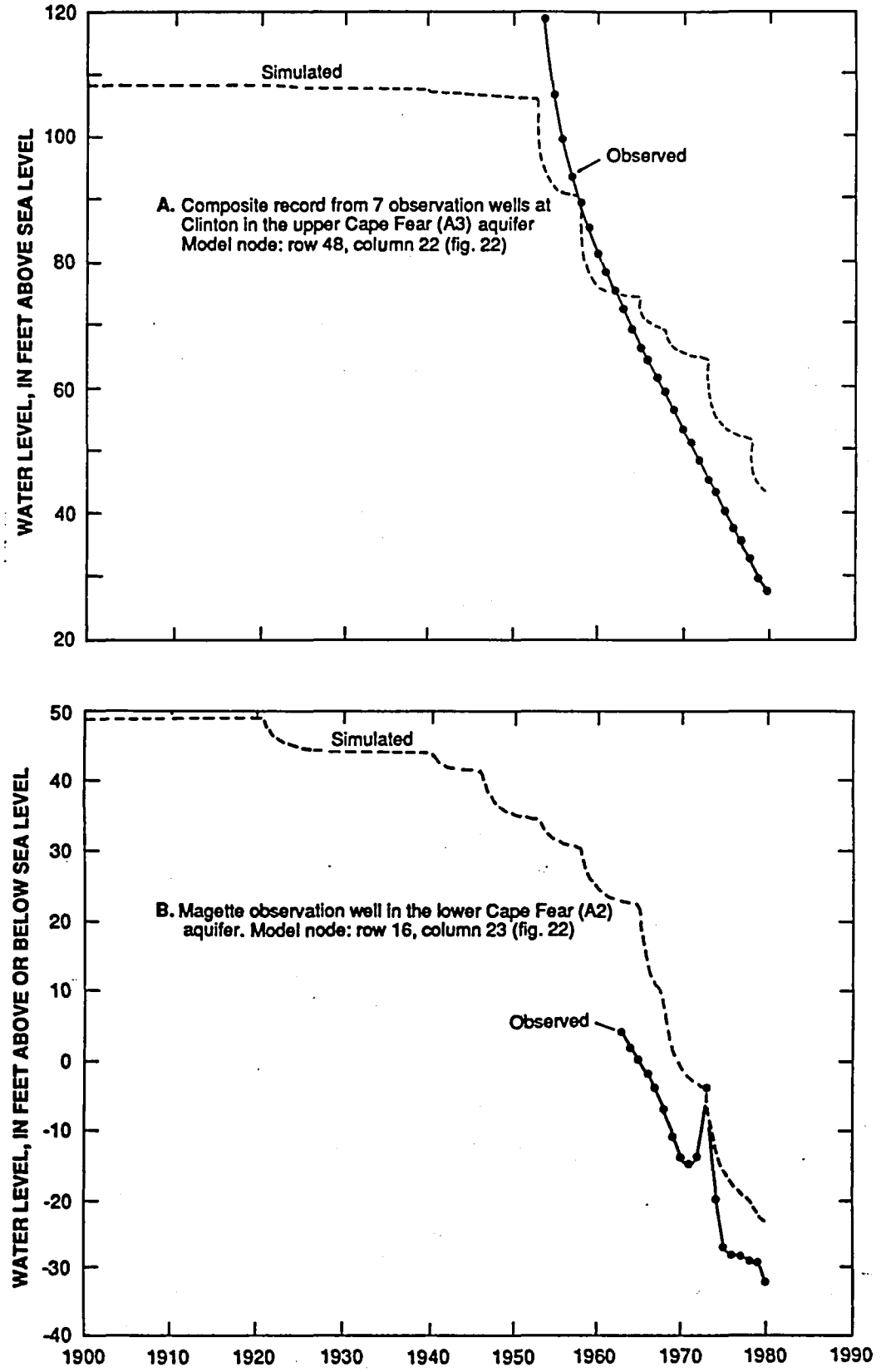


Figure 69.--Observed and simulated water levels in the (A) upper Cape Fear and (B) lower Cape Fear aquifers.

One measure of the degree to which the model can be considered calibrated is the density of calibration points that were used. By this criterion, the Castle Hayne aquifer (A7) would be considered the best calibrated layer (particularly near the large cone of depression centered just north of Aurora in Beaufort County), whereas the Lower Cretaceous, Beaufort, and Pungo River aquifers (A1, A6, and A8) would be among the least well calibrated.

The Cape Fear Arch Saltwater Reentrant

An unusual landward reentrant of water containing high chloride concentrations (equal to or greater than 10,000 mg/L) has been delineated in the Wilmington area by Winner and Coble (1989) in the upper and lower Cape Fear aquifers (A2 and A3). This reentrant is shown in figures 32 and 33 by the northwestward bulge or point in the 10,000 mg/L chloride concentration line, which is considered to be a no-flow boundary in this study. The existence of the reentrant is supported by the work of LeGrand (1955) who described brackish water springs more than 20 ft above sea level as far inland as Bladen County, and by Meisler (1981) who mapped the position of the saltwater in aquifers of the North Atlantic Coastal Plain. The reentrant overlies the Cape Fear Arch, which is a broad southeast trending uplift of both bedrock and the overlying sedimentary deposits of the Atlantic Coastal Plain (fig. 8). The axis of the uplift is marked approximately by the course of the lower Cape Fear River.

Trial simulations performed during model calibration indicated that barrier to flow was needed to sustain the unusually high heads in the aquifers in extreme southeastern North Carolina (Peek and 1975) and even higher heads further south along the South Carolina Aucott and Speiran, 1985). A barrier might result from the aquifers lower transmissivity in the Cape Fear Arch area than in surrounding the juxtaposition of such a barrier over the Arch suggests that the have affected depositional patterns in the area during Cretaceous in deposition of sediments of extremely low transmissivity, low hydraulic conductivity or near zero thickness, in the position of the upper and lower Cape Fear aquifers. However, the few wells in the Arch area listed by Winner and Coble (1989) of only small reductions in transmissivity of these two

The lower Cape Fear aquifer (A2), which exhibits the highest heads, is slightly thinner on the northeast side of the Cape Fear Arch than on the southwest side (fig. 8), but does not thin enough to cause a major change in transmissivity at this location. The upper Cape Fear aquifer (A3) has lower transmissivity on the northeast side of the Arch than on the southwest side; this results from lower hydraulic conductivity in this area (Winner and Coble, 1989) not a decrease in thickness as might be the case for the lower Cape Fear aquifer (A2). The trial simulations revealed that in order to sustain the high heads in the lower Cape Fear aquifer (A2) southwest of the Arch, a no-flow or nearly no-flow boundary had to be present in the general area occupied by the saltwater reentrants shown in figures 32 and 33. Adjustment of transmissivity values of the lower Cape Fear aquifer (A2) over the Arch to 50 percent or less of estimated values (fig. 33) resulted in little head buildup southwest of the Arch.

Because there is no direct hydrogeologic evidence indicating a drastic change in the hydraulic conductivity or thickness of the upper and lower Cape Fear aquifers, it may be that the no-flow boundary results instead from the presence of dense water containing at least 10,000 mg/L chloride over the Cape Fear Arch. The confirmation of either idea (or other ideas) concerning the nature of the flow barrier (low-transmissivity sediments or saltwater) awaits further data and analyses for support.

Sensitivity Analysis

Two types of applications of sensitivity analyses are appropriate in modeling studies. The first application is logically performed before model calibration to aid in data collection. If this analysis shows that the model is not sensitive to changes in certain parameters in part of the modeled area, efforts to improve parameter estimates there would not improve the simulation capability of the model. Conversely, if the initial sensitivity analysis shows that the model is sensitive to changes in a particular parameter in an area, data-collection activities and analyses to better define or verify the parameter values in that area could result in improved simulation capability.

A second application is performed after calibration to evaluate the relation between parameter variability and model response. This is an indication of the extent to which calibration is likely to have improved parameter estimates and may be a guide in the design of parameter-estimation efforts for future modeling studies. The following sections discuss this second application of the sensitivity analysis during this study.

Method of Analysis

The model response investigated in the sensitivity analysis was hydraulic head. The parameters selected for testing were transmissivity, storage coefficient of aquifers, and leakance of confining units. Transmissivity and leakance values were varied by plus and minus 50 percent and plus and minus 90 percent of their estimated values. Storage coefficient was varied by plus and minus 90 percent of its estimated value.

To minimize computer time required for the analysis of transmissivity and leakance, steady-state simulations utilizing 1980 pumpage values were made. However, as in transient simulations performed for calibration purposes, streams were simulated as a constant head layer and the surficial aquifer (A10) was simulated as a free surface receiving recharge. Tests showed that heads computed in this manner were similar to 1980 heads computed by transient simulations, indicating that steady-state simulations made as a part of the sensitivity analysis would provide results similar to transient simulations. However, transient simulations (1900-1980) were made to analyze the effects of varying storage coefficient, because these results were more time dependent.

To simplify the sensitivity analysis, the aquifers and confining units were grouped into three groups of hydrologically-similar flow systems. Group 1 consisted of the Peedee (A5), Black Creek (A4), upper Cape Fear (A3), lower Cape Fear (A2), and Lower Cretaceous (A1) aquifers, which are the sand aquifers in Cretaceous rocks. Group 2 included the Yorktown (A9), Pungo River (A8), and Beaufort (A6) aquifers, sand aquifers in Tertiary rocks, and in analyzing aquifer parameters, the surficial aquifer (A10). When analyzing a confining unit parameter, the surficial aquifer (A10) was not included. Group 3 was solely the Castle Hayne aquifer (A7), which is

primarily limestone and sand of Tertiary age. Parameters were perturbed and analyzed for each group. The exception was storage coefficient; for this parameter, all model layers were perturbed and analyzed simultaneously.

Results

Tables 5 and 6 list the mean values (calibrated values) and maximum and minimum values of the parameter variations for the three aquifer groups for transmissivity, leakance, and storage coefficient. Within each of the three aquifer groups, the results of the sensitivity analysis were categorized and statistics generated separately for each category. These categories are (1) all active nodes, (2) nodes where pumpage occurred (pumpage nodes), (3) nodes with no flow in a laterally-adjacent node, (4) nodes with constant flux in a laterally-adjacent node, and (5) nodes with constant head in a vertically-adjacent node, (category 5 is found only in the surficial aquifer (A10) in group 2). If a given node fell into more than one category, the node was omitted from the analysis in all but the active-node category. The overall results of the sensitivity analysis are summarized in table 7.

Table 5.--*Range of perturbed values for transmissivity and leakance*

Value	Group 1	Group 2	Group 3
Transmissivity, in feet squared per day			
Mean	2,994	1,758	33,030
10 percent of mean	299	176	3,303
190 percent of mean	5,688	3,340	62,757
Leakance, per day			
Mean	3.8×10^{-5}	2.3×10^{-2}	4.8×10^{-3}
10 percent of mean	3.8×10^{-6}	2.3×10^{-3}	4.8×10^{-4}
190 percent of mean	7.2×10^{-5}	4.37×10^{-2}	9.12×10^{-3}

Table 7 indicates a general tendency for the Cretaceous sand aquifers (group 1) to exhibit a greater degree of head variation for a given percentage change in model parameter than the other groups. This is mainly attributed to group 1 nodes representing the deep Cretaceous aquifers with the least hydraulic contact with the surficial aquifer (A10). The surficial aquifer is resistant to changes in head for several reasons. First, being unconfined, it has a much larger storage coefficient than the lower confined

Table 6.--*Range of perturbed values for storage coefficient*

Value	All groups
Confined aquifer (dimensionless)	
Mean	1.0×10^{-4}
10 percent of mean	1.0×10^{-5}
190 percent of mean	1.9×10^{-4}
Unconfined aquifer (dimensionless)	
Mean	1.5×10^{-1}
10 percent of mean	1.5×10^{-2}
190 percent of mean	2.8×10^{-1}

aquifers. Second, in the various simulation schemes described earlier, it either receives direct recharge in large amounts or the water table is treated as a constant head surface. Normally, most of this recharge goes to stream nodes with only a small amount recharging the deeper aquifers. However, if the water levels in the surficial aquifer start to decline, less of this recharge will go to streams, and more is available to sustain the water level in the surficial aquifer and recharge the deeper aquifers. Further, if the water level is drawn down below stream levels, then the streams recharge the surficial aquifer. Thus, the surficial aquifer and aquifers in close hydraulic contact with it tend to show the least sensitivity to changes in model parameters. Table 7 also indicates that pumpage nodes are the most sensitive to parameter changes. This indicates that future ground-water flow modeling studies could best concentrate parameter estimation efforts in areas being pumped.

Generally, the model was found to be highly sensitive to changes in transmissivity and leakance near pumping centers. Away from pumping centers, the model was only slightly sensitive to transmissivity changes but highly sensitive to changes in leakance (compare mean values for head [illegible] for all active nodes for transmissivity and leakance in table 7).

The greatest head difference in the sensitivity analysis was for transmissivity in the Cretaceous aquifers (group 1), where a decrease in [illegible] more than 900 ft occurred at one pumping node in the Black Creek [illegible] (A4) when transmissivity was reduced by 90-percent (fig. 70A).

Table 7.--*Results of sensitivity analysis*

Parameter	Category of nodes tested		Head change, in feet, for indicated percent change in parameters											
			Group 1				Group 2				Group 3			
			-90 percent	-50 percent	+50 percent	+90 percent	-90 percent	-50 percent	+50 percent	+90 percent	-90 percent	-50 percent	+50 percent	+90 percent
Transmissivity (T)	All active nodes	Max (+)	105	18.1	53.3	77.6	12.0	5.24	3.70	5.83	15.7	5.59	28.6	32.4
		Mean	-12.6	-5.05	3.53	5.75	-.01	.004	.001	.002	-.50	-.32	.18	.42
		Max (-)	-907	-138	-12.0	-19.2	-18.0	-6.24	-4.52	-7.70	-465	-75.7	-24.2	-4.15
	Pumping node	Max (+)	6.01	2.74	53.3	77.6	.76	.36	.67	1.09	11.7	4.28	28.6	32.4
		Mean	-91.8	-16.7	7.59	11.5	-.87	-.36	.26	.42	-18.3	-3.17	1.30	1.56
		Max (-)	-907	-138	-2.07	-3.17	-4.53	-1.33	-.27	-.46	-465	-75.6	-2.46	-2.82
	Adjacent to no flow node	Max (+)	71.9	18.1	22.1	32.2	4.52	2.13	1.31	2.22	2.24	1.14	1.02	1.20
		Mean	-6.85	-3.54	2.70	4.43	.11	-.05	-.05	-.08	.14	.06	-.06	-.06
		Max (-)	-415	-59.5	-12.0	-19.2	-3.05	-1.56	-1.70	-2.78	-2.68	-1.32	-1.03	-1.23
	Adjacent to constant flux node	Max (+)	105	15.1	27.6	41.2	4.33	2.49	1.70	2.78	1.31	.65	.78	1.05
		Mean	-38.4	-11.0	6.60	10.5	-.27	-.10	.07	.11	-.09	-.18	.26	.36
		Max (-)	-344	-63.5	-6.58	-10.7	-5.85	-2.26	-2.25	-3.86	-2.49	-.96	-.52	-.62
	Vertically adjacent to constant head node	Max (+)	--	--	--	--	10.0	5.24	1.87	3.25	--	--	--	--
		Mean	--	--	--	--	.09	-.05	-.04	-.08	--	--	--	--
		Max (-)	--	--	--	--	-3.76	-2.03	-4.52	-7.70	--	--	--	--

Table 7.--*Results of sensitivity analysis*--Continued

Parameter	Category of nodes tested		Head change, in feet, for indicated percent change in parameters											
			Group 1				Group 2				Group 3			
			-90 percent	-50 percent	+50 percent	+90 percent	-90 percent	-50 percent	+50 percent	+90 percent	-90 percent	-50 percent	+50 percent	+90 percent
Leakance (TX)	All active nodes	Max (+)	37.2	13.2	22.6	32.9	12.9	7.00	4.28	6.54	4.06	1.96	6.70	9.60
		Mean	-78.1	-11.7	4.36	6.30	-4.28	-.47	.15	.21	-8.75	-1.61	.64	.94
		Max (-)	-361	-57.3	-6.80	-10.2	-38.2	-8.59	-5.08	-8.34	-114	-18.5	-1.25	-1.99
	Pumping node	Max (+)	.19	.08	18.0	27.0	0	.11	1.99	2.95	1.57	.96	6.70	9.60
		Mean	-79.8	-14.8	6.50	9.71	-6.27	-.94	.35	.51	-11.1	-2.17	.92	1.38
		Max (-)	-284	-44.9	-.03	-.06	-19.4	-4.45	-.05	-.08	-114	-18.5	-.72	-1.16
	Adjacent to no flow node	Max (+)	16.7	5.70	22.6	32.9	4.90	2.11	3.08	4.58	2.82	1.00	1.53	2.19
		Mean	-79.4	-10.7	3.68	5.21	-3.77	-.41	.15	.21	-3.79	-.36	.10	.14
		Max (-)	-361	-57.2	-4.05	-7.25	-29.5	-6.51	-.89	-1.30	-19.4	-3.74	-.57	-.83
	Adjacent to constant flux node	Max (+)	26.8	11.8	22.6	32.9	2.92	.65	4.24	6.47	1.30	.44	1.75	2.55
		Mean	-94.7	-12.9	4.41	6.26	-4.92	-.75	.30	.44	-6.21	-.81	.20	.25
		Max (-)	-361	-57.3	-6.66	-10.2	-38.2	-8.59	-.39	-.61	-20.2	-4.19	-.28	-.44
	Vertically adjacent to constant head node	Max (+)	--	--	--	--	--	--	--	--	--	--	--	--
		Mean	--	--	--	--	--	--	--	--	--	--	--	--
		Max (-)	--	--	--	--	--	--	--	--	--	--	--	--

Table 7.--*Results of sensitivity analysis*--Continued

Parameter	Category of nodes tested		Head change, in feet, for indicated percent change in parameters											
			Group 1				Group 2				Group 3			
			-90 percent	-50 percent	+50 percent	+90 percent	-90 percent	-50 percent	+50 percent	+90 percent	-90 percent	-50 percent	+50 percent	+90 percent
Storage coefficient (SC)	All active nodes	Max (+)	0.01	--	--	5.57	0.12	--	--	3.14	0.11	--	--	0.32
		Mean	-.67	--	--	1.15	-.02	--	--	.03	-.01	--	--	.02
		Max (-)	-7.37	--	--	-.04	-3.54	--	--	-.04	-.28	--	--	-.03
	Pumping node	Max (+)	0	--	--	3.13	.02	--	--	-.12	.11	--	--	.21
		Mean	-.68	--	--	.91	-.01	--	--	.03	-.02	--	--	.03
		Max (-)	-3.53	--	--	.07	-.06	--	--	-.01	-.22	--	--	-.01
	Adjacent to no flow node	Max (+)	.01	--	--	4.15	0	--	--	.15	.002	--	--	.07
		Mean	-.62	--	--	1.15	-.01	--	--	.02	-.01	--	--	.01
		Max (-)	-2.47	--	--	-.04	-.09	--	--	-.01	-.09	--	--	0
	Adjacent to constant flux node	Max (+)	0	--	--	2.75	.001	--	--	.38	0	--	--	.08
		Mean	-.49	--	--	.94	-.02	--	--	.05	-.01	--	--	.02
		Max (-)	-1.42	--	--	.01	-.18	--	--	-.01	-.04	--	--	.001
	Vertically adjacent to constant head node	Max (+)	0	--	--	0	.12	--	--	3.14	0	--	--	0
		Mean	0	--	--	0	-.02	--	--	.02	0	--	--	0
		Max (-)	0	--	--	0	-3.54	--	--	-.03	0	--	--	0

Increases in transmissivity and leakance (fig. 70A and 70B) produced smaller head changes than similar percentage decreases in these parameters, whereas increases in storage coefficient (fig: 70C) produced similar or sometimes greater changes in head than corresponding decreases.

Sensitivity analyses results on other subregional models in the northeast Atlantic Coastal Plain were similar to the type of model responses reported here. Some effects of parameter changes studied in the sensitivity analyses of Virginia and New Jersey model studies were not studied in North Carolina, such as confining-unit storage, position of the freshwater-saltwater no-flow boundary, boundary fluxes, and recharge (Harsh and Laczniak, 1990, and Martin, 1990). However, because of the similarity of the models, similar responses might be expected for the North Carolina model.

In New Jersey and Virginia, confining-unit storage was shown to be important to simulation of the system when the response of confining units is in the range of inelastic deformation. The Virginia and New Jersey models were not sensitive to the position of the freshwater-saltwater no-flow boundary. However, unlike North Carolina, these States have no significant pumpage affecting areas near the freshwater-saltwater no-flow boundary. The New Jersey model was sensitive to boundary flux near the boundaries, but not sensitive to boundary fluxes two or three nodes away from the boundaries. The Virginia and New Jersey models' insensitivity to recharge was similar to that for the North Carolina flow model. Results indicate that all the models were not sensitive to changes in recharge rate to the surficial aquifer in transient simulations, because streambed leakance was increased or decreased to move more or less water into streams to balance increases or decreases in recharge (refer to streambed leakance section of report under Model Input).

HYDROLOGIC ANALYSIS OF THE AQUIFER SYSTEM

Water Budget

Most aspects of the overall ground-water flow system have not changed significantly from predevelopment conditions in 1900 to development

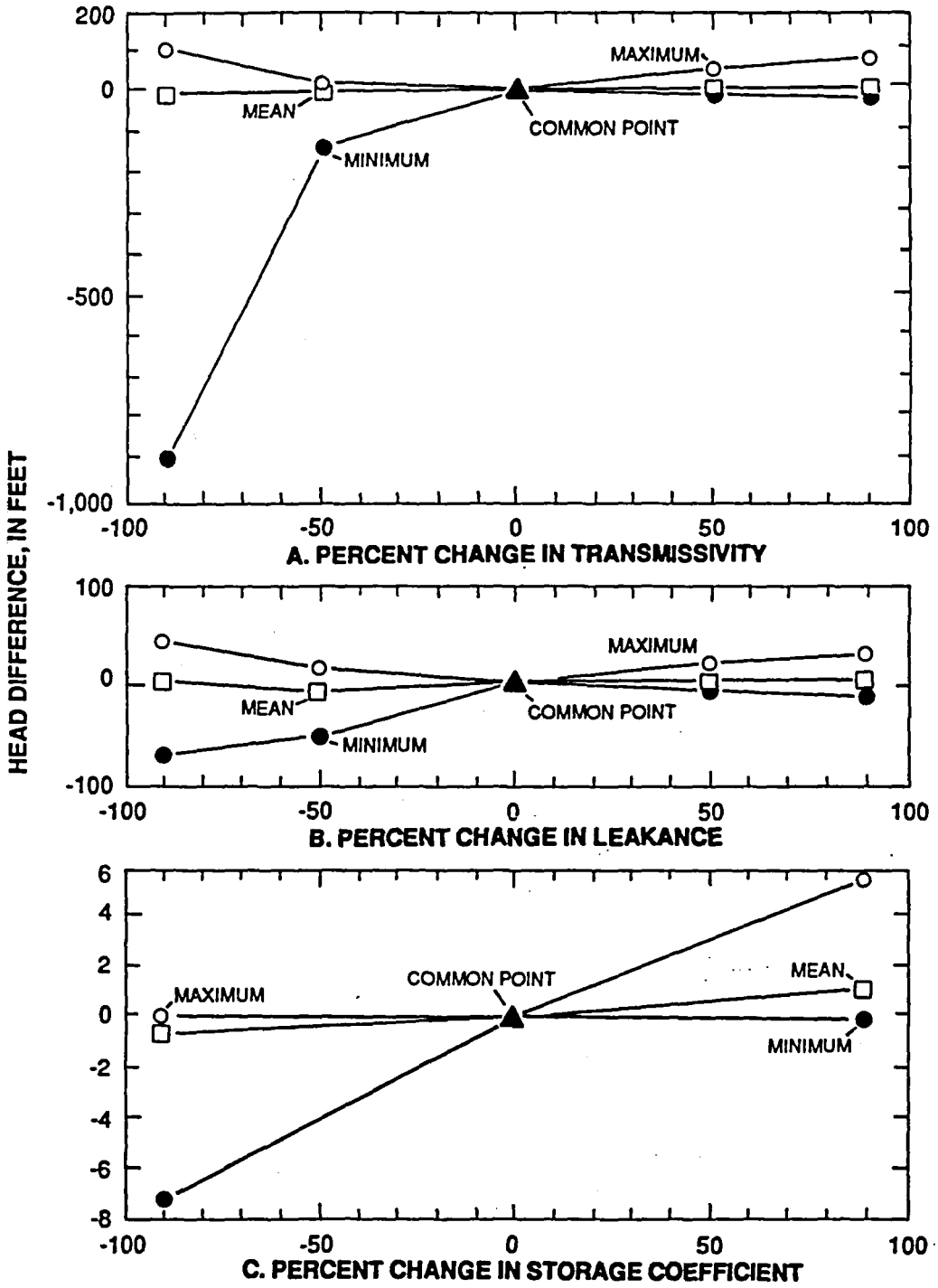


Figure 70.--Head differences in Cretaceous sand aquifers (group 1) due to changes in (A) group 1 transmissivity, (B) group 1 leakance, and (C) model-wide storage coefficient.

conditions in 1980. The only major change on the system during that time interval has been initiation and continued increase of ground-water withdrawals. Pumpage in North Carolina and in nearby southeastern Virginia has altered the overall water budget very little, although local effects are significant. Pumpage from large areas in North Carolina increased from zero before 1900 to 302 ft^3/s (cubic feet per second) (195 Mgal/d) in 1980, which is only about 1.1 percent of the average recharge to the ground-water system of 25,703 ft^3/s (table 8).

Simulation results indicate that pumpage from the ground-water system over time is ultimately compensated for largely by reduced flow to streams. Reduction in flow to streams between 1900 and 1980 over the entire Coastal Plain, shown as constant-head discharge from the system in table 8, was 297 ft^3/s and, although not large in relation to the total of the average flow of all the Coastal Plain streams, could locally be a significant percentage of dry-weather streamflow in some streams.

Major changes in the amount of water withdrawn from wells (fig. 54 and table 8) have resulted in changes in contributions from ground-water storage as favorable hydraulic gradients are established toward pumping centers. When these gradients are established and if there is sufficient recharge, a new equilibrium condition will be reached in which contributions from storage to pumpage will be negligible. Significant withdrawals from the sand aquifers of Cretaceous age began during 1940-45. At that time contributions from storage amounted to several cubic feet per second. By 1965-67 withdrawals from the Castle Hayne aquifer (A7) increased, and storage contributions increased to 20 ft^3/s. During 1968-80, the contributions from storage resulting from withdrawals from the Castle Hayne aquifer were small as equilibrium was again established, but increased withdrawals elsewhere, primarily in sand aquifers of Cretaceous age, caused an increase in total contributions from storage of about 14 ft^3/s.

Pumpage has changed ground-water movement within the system, but change in recharge and discharge to the system has been slight. The average recharge rate of 25,703 ft^3/s was calculated as a constant over the simulation period. Natural discharge from the system as base flow to streams and discharge to the sounds decreased slightly from 25,701 to 25,404

Table 8.--*Summary of model-computed water budgets for the ground-water flow system of the North Carolina Coastal Plain, 1900-2000*

Pumping period	Dates	Flow rates to (+) and from (-) flow system at end of pumping period, in cubic feet per second							
		Change in storage	Recharge	Specified flux		Pumping	Constant head		Difference between inflow and outflow
				to system	from system		to system	from system	
Prepumping	Pre-1900	0	+25,703	+10	-15.0	0	+0.5	-25,701	-2.5
1	Jan. 1, 1900-Dec. 31, 1920	- .1	+25,703	+10	-15.3	-4.7	+ .5	-25,697	-3.6
2	Jan. 1, 1921-Dec. 31, 1939	+ .2	+25,703	+8	-15.3	-11.8	+ .5	-25,688	-3.4
3	Jan. 1, 1940-Dec. 31, 1945	+4	+25,703	+8	-32.9	-16.1	+ .5	-25,670	-3.5
4	Jan. 1, 1946-Dec. 31, 1952	+6	+25,703	+7	-18.4	-62.6	+1.5	-25,641	-4.5
5	Jan. 1, 1953-Dec. 31, 1957	+7	+25,703	+7	-18.8	-77.2	+2.1	-25,627	-3.9
6	Jan. 1, 1958-Dec. 31, 1964	+6	+25,703	+7	-20.7	-125.3	+14.9	-25,588	-3.1
7	Jan. 1, 1965-Dec. 31, 1967	+20	+25,703	+7	-34.5	-197.5	+3.6	-25,504	-2.4
8	Jan. 1, 1968-Dec. 31, 1972	+14	+25,703	+8	-28.8	-242.2	+4.0	-25,460	-2.0
9	Jan. 1, 1973-Dec. 31, 1977	+14	+25,703	+8	-36.7	-275.3	+5.7	-25,422	-3.3
10	Jan. 1, 1978-Dec. 31, 1980	+14	+25,703	+8	-36	-294	+5.9	-25,404	-3.1
	Simulated year 2000	+26	+25,703	+8	-21	-531	+42.1	-25,229	-1.9

ft^3/s from pre-1900 to 1980, a decrease of 297 ft^3/s or less than 1.2 percent of the total recharge. Pumpage was mainly supplied by this diversion. The change in natural discharge of 297 ft^3/s is very close to the rate of pumping during the 1978-80 pumping period (294 ft^3/s). The excess decrease in natural discharge of 3 ft^3/s is mostly due to effects of pumpage in adjacent States, primarily Virginia.

The principal change in the North Carolina Coastal Plain ground-water flow system primarily involves vertical movement of water from one layer in the system into another in and around those areas where the major pumping is taking place. The changes in direction of vertical flow are shown by a series of maps presented in a following section of this report.

Loss of ground-water storage is sensitive to the rate of pumping increase. Rate of loss of storage was greatest (20 ft^3/s) during 1965-67 when withdrawals increased an average of 24.1 ft^3/s per year. Since then, the contribution from storage has remained at 14 ft^3/s as withdrawal increases have been fairly constant, averaging 7.4 ft^3/s.

Simulated ground-water flow across the Virginia and South Carolina borders changed significantly from 1900 to 1980. The most dramatic change was across the Virginia line where 3.8 ft^3/s flowed from Virginia to North Carolina in 1900; by 1980 ground-water flow was from North Carolina to Virginia at a rate of 24.7 ft^3/s. This change occurred in the lower Cape Fear aquifer (A2) and, to a lesser extent, in the upper Cape Fear aquifer (A3) and Lower Cretaceous aquifers (A1). The change results from pumpage mainly from the lower Cape Fear aquifer (A2) and Lower Cretaceous aquifer (A1) at Franklin, Virginia, which is about 25 miles north of Ahoskie, North Carolina.

Flow from North Carolina to South Carolina was 7.1 ft^3/s in 1900, and decreased slightly to 6.4 ft^3/s in 1980. This decrease is attributed pumpage in the southern Coastal Plain of North Carolina from the Black (A4) and lower Cape Fear (A3) aquifers. A slight lowering of the potentiometric surfaces of these two aquifers in North Carolina decreased hydraulic gradient toward South Carolina.

A model simulation was made for the year 2000 with the assumption that pumping would increase by 3 percent per year from 1981 to 2000. Under these conditions, contributions from storage would nearly double as cones of depression in the sand aquifers of Cretaceous age continue to increase in size, and contributions from streams (induced infiltration) would increase nearly 7-fold from those of 1980. Ground-water discharge to streams would continue but at a very slightly decreased rate.

Potentiometric Surfaces

Although changes in the overall water budget for the Coastal Plain aquifers due to pumping were minor during 1900-80, pumping has caused large local decreases in the potentiometric surfaces of several aquifers. In order to show the changes in the potentiometric surfaces of the 10 aquifers, maps are presented for the simulated prepumping condition (1900), for 1980 conditions, and for assumed pumping conditions in the year 2000.

Simulated prepumping potentiometric surfaces are shown for the 10 aquifers in figures 71 through 80. The figures also show available observed water-level values for the late 1800's and early 1900's in unpumped areas. Many of these water-level observations were taken from Clark and others (1912) and from unpublished drillers' records from that era. In some instances, modern water levels are shown in these figures and were assumed to represent prepumping conditions in aquifers unaffected by pumping, such as for the lower Cape Fear aquifer (A2) (fig. 79) in the southern part of the Coastal Plain. The potentiometric surfaces for the surficial aquifer (A10) and for the updip (western) parts of all the other aquifers are high in the interstream divide areas and low in the valleys of perennial streams. This indicates that for these aquifers in these areas most ground-water movement is within local flow systems, and most ground-water discharge is to the nearby streams. In the downdip areas of confined aquifers, the Yorktown through Lower Cretaceous aquifers (A9-A1), the potentiometric surfaces have a gentle coastward gradient to the east-southeast.

Simulated potentiometric surfaces for 1980 (figs. 81 through 90) when compared to 1900 prepumping potentiometric surfaces (figs. 71-80) indicate lowered water levels in parts of most aquifers due to pumping. Notably,

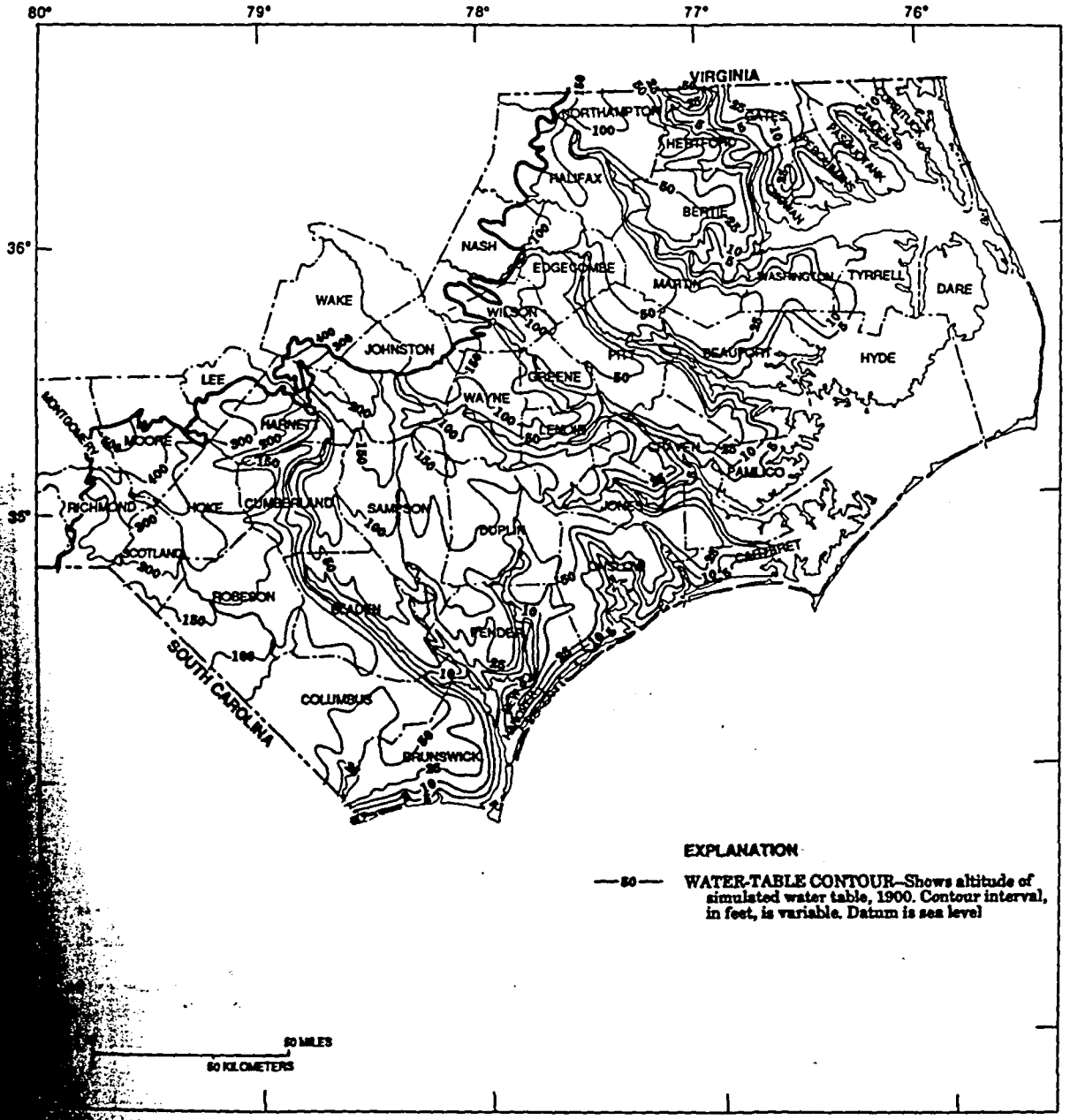


Figure 71.--Simulated prepumping (1900) water table for the surficial aquifer (A10).

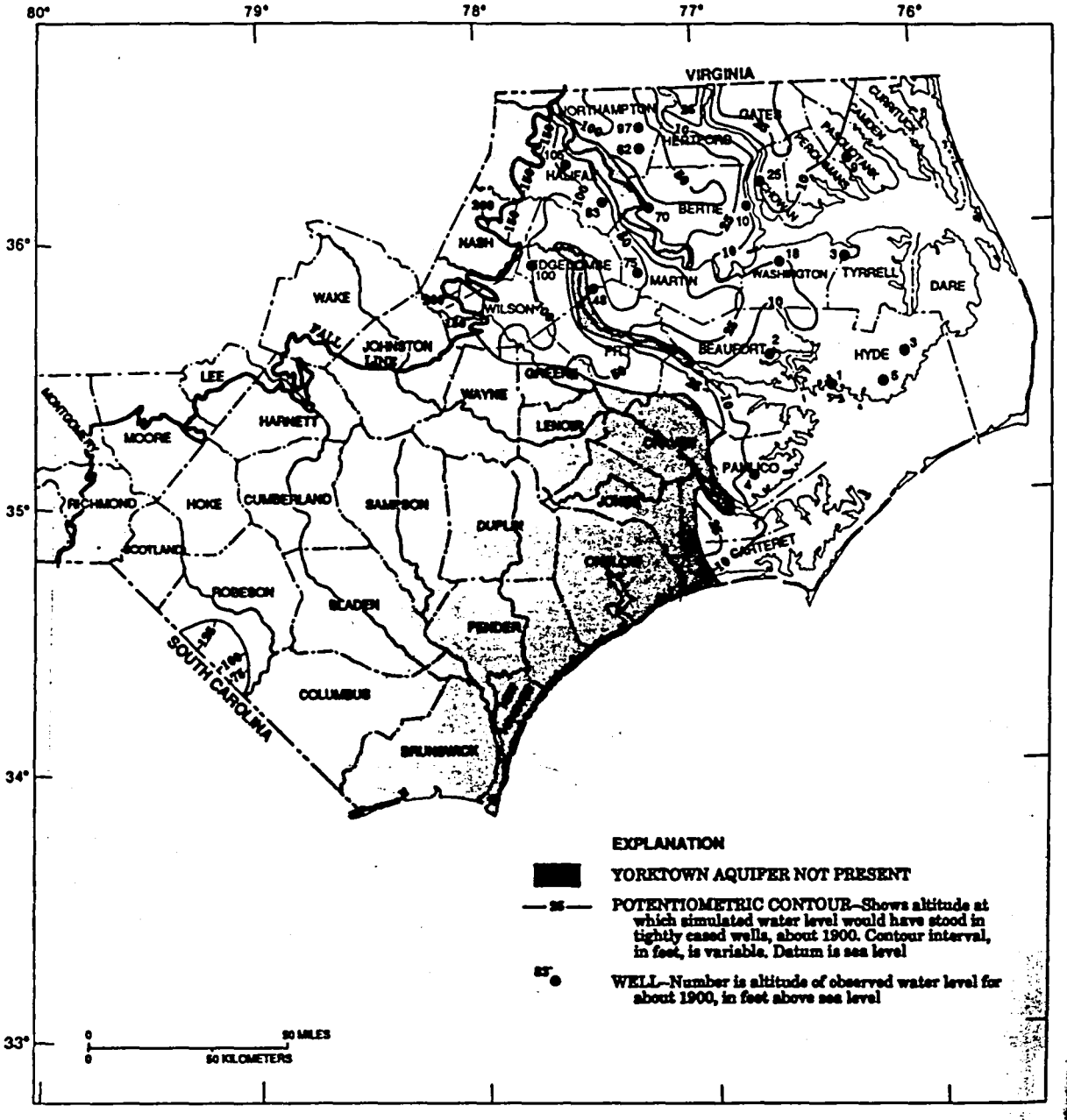


Figure 72.--Simulated prepumping (1900) potentiometric surface for the Yorktown aquifer (A9).

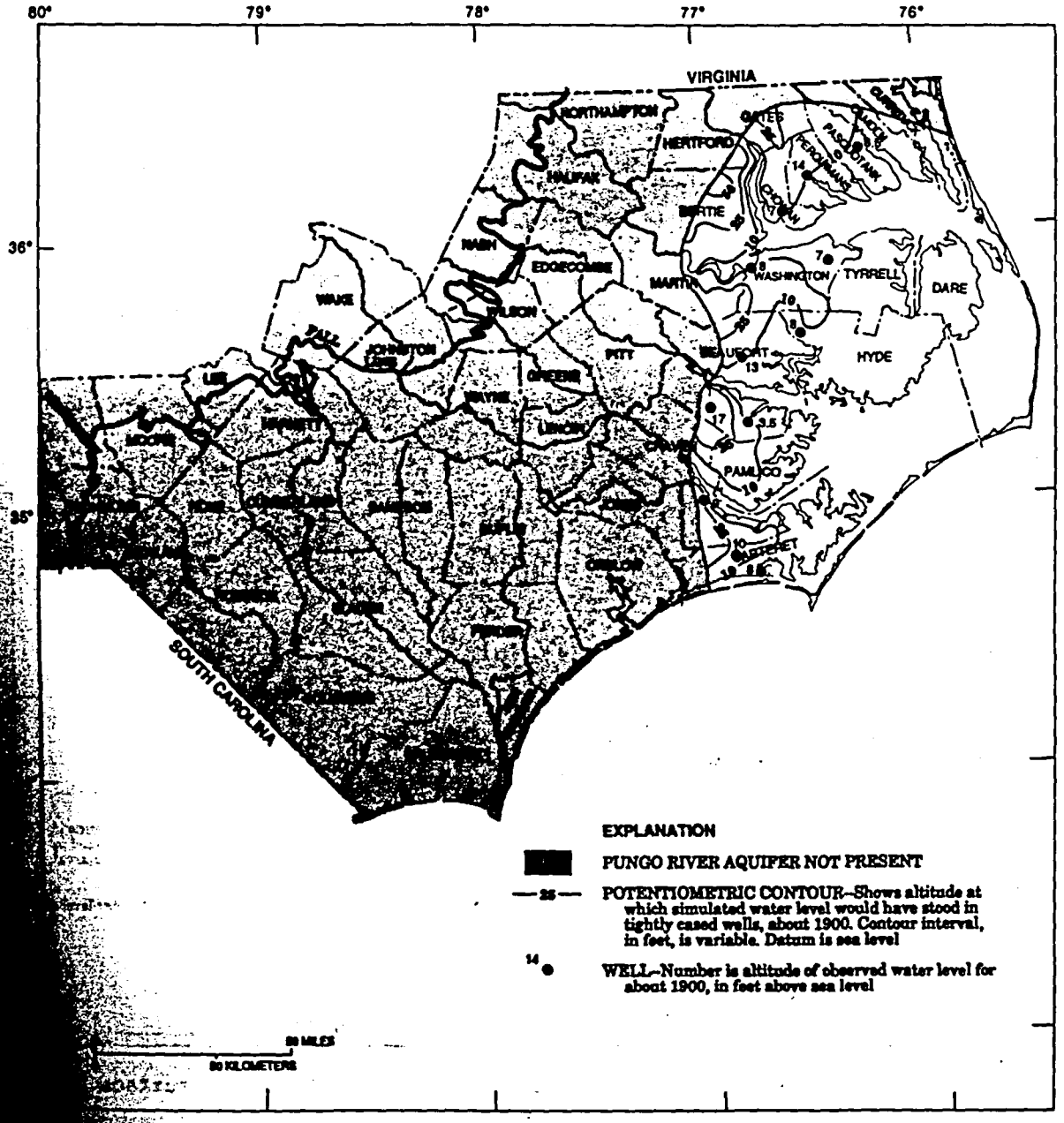


Figure 73.--Simulated prepumping (1900) potentiometric surface for the Pungo River aquifer (A8).

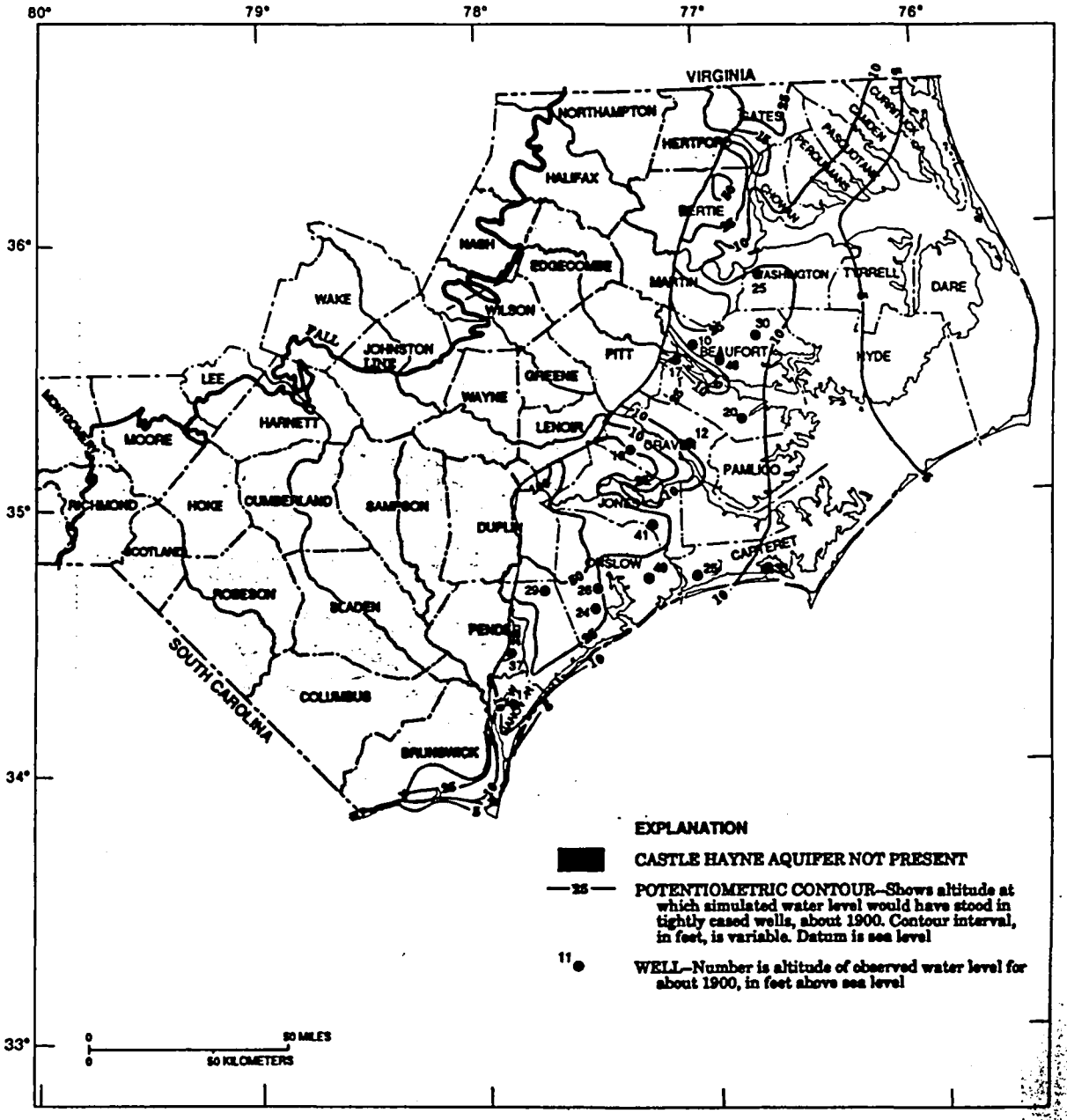


Figure 74.--Simulated prepumping (1900) potentiometric surface for the Castle Hayne aquifer (A7).

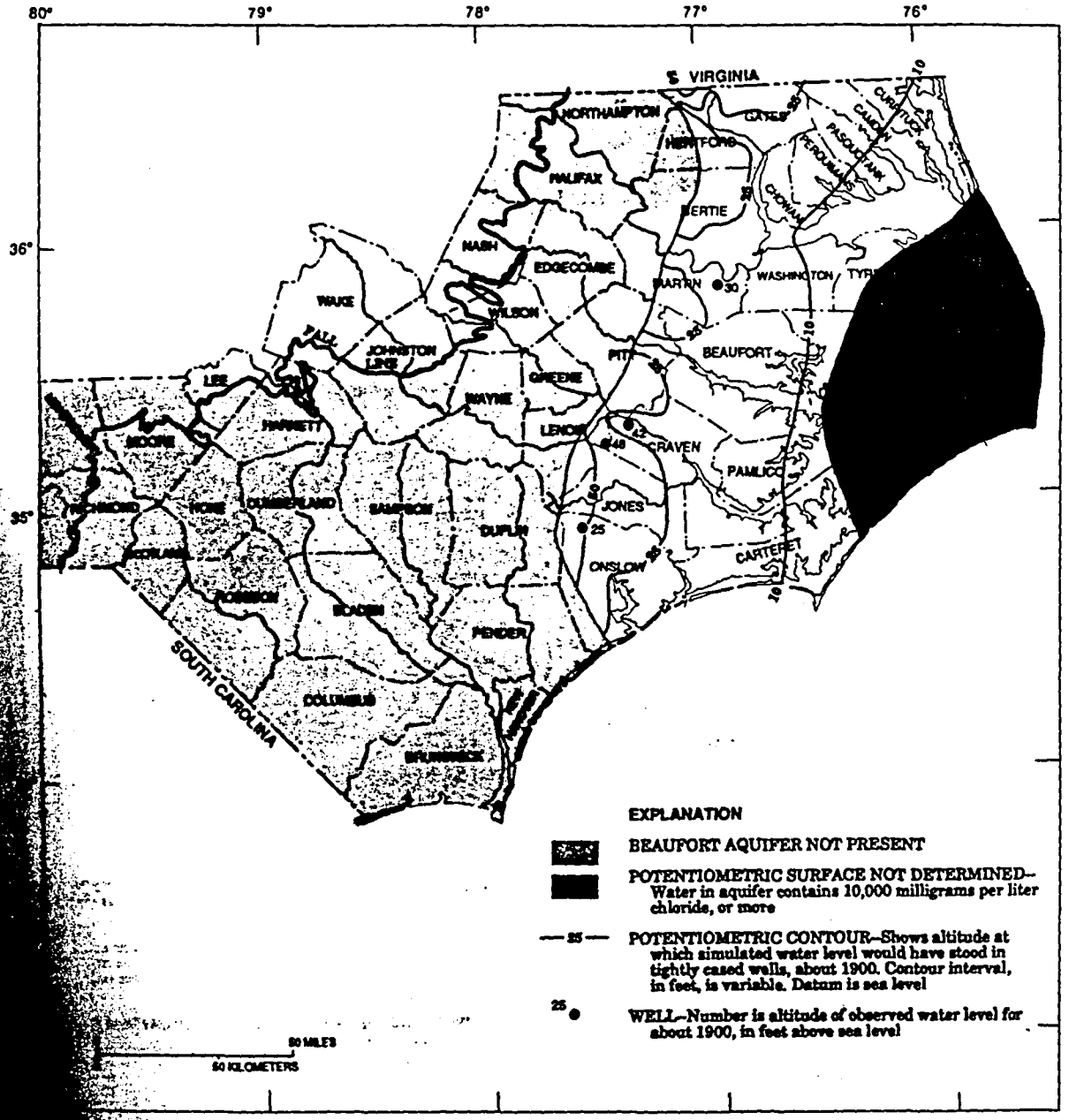


Figure 75.--Simulated prepumping (1900) potentiometric surface for the Beaufort aquifer (A6).

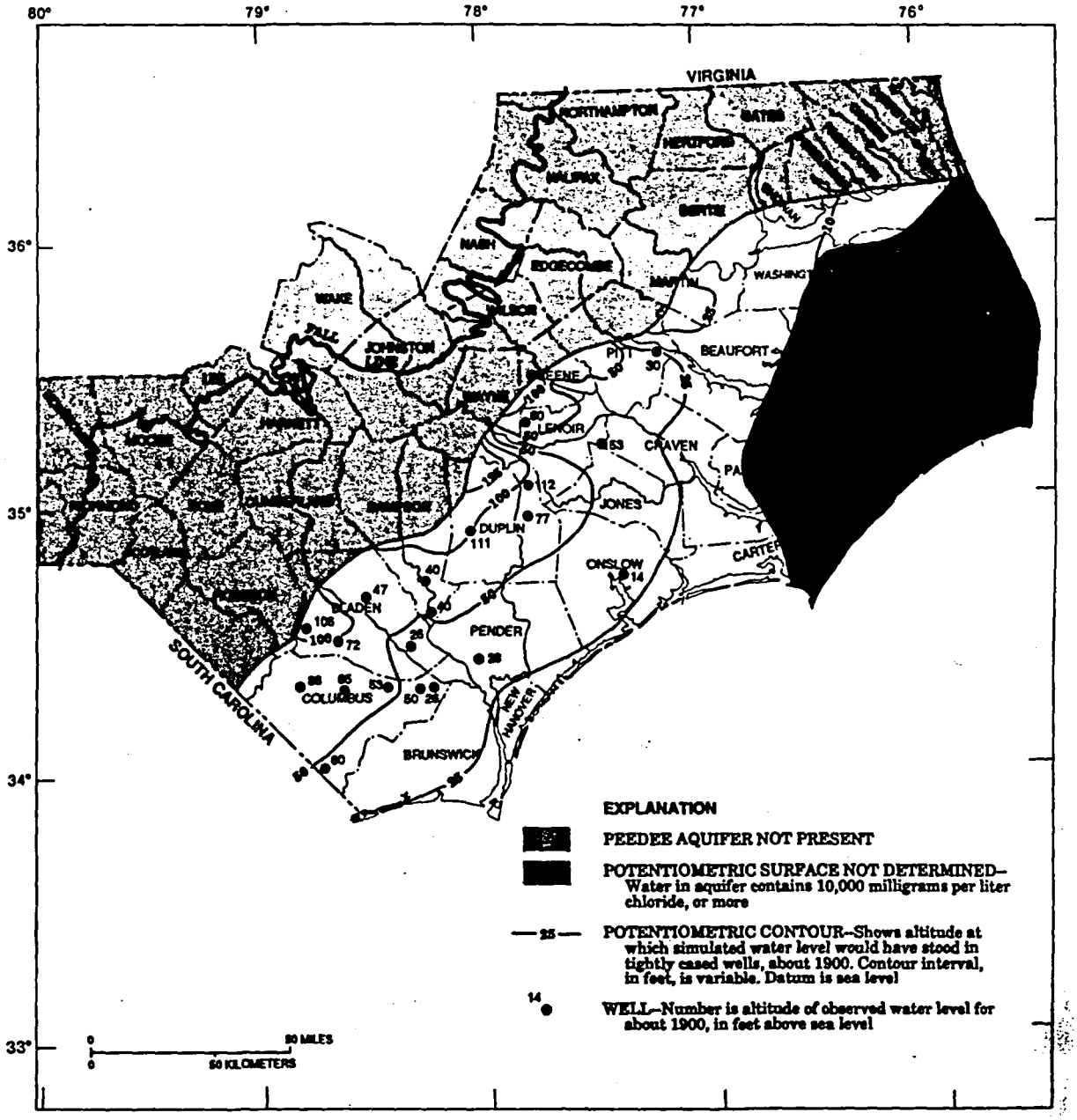


Figure 76.--Simulated prepumping (1900) potentiometric surface for the Peedee aquifer (A5).

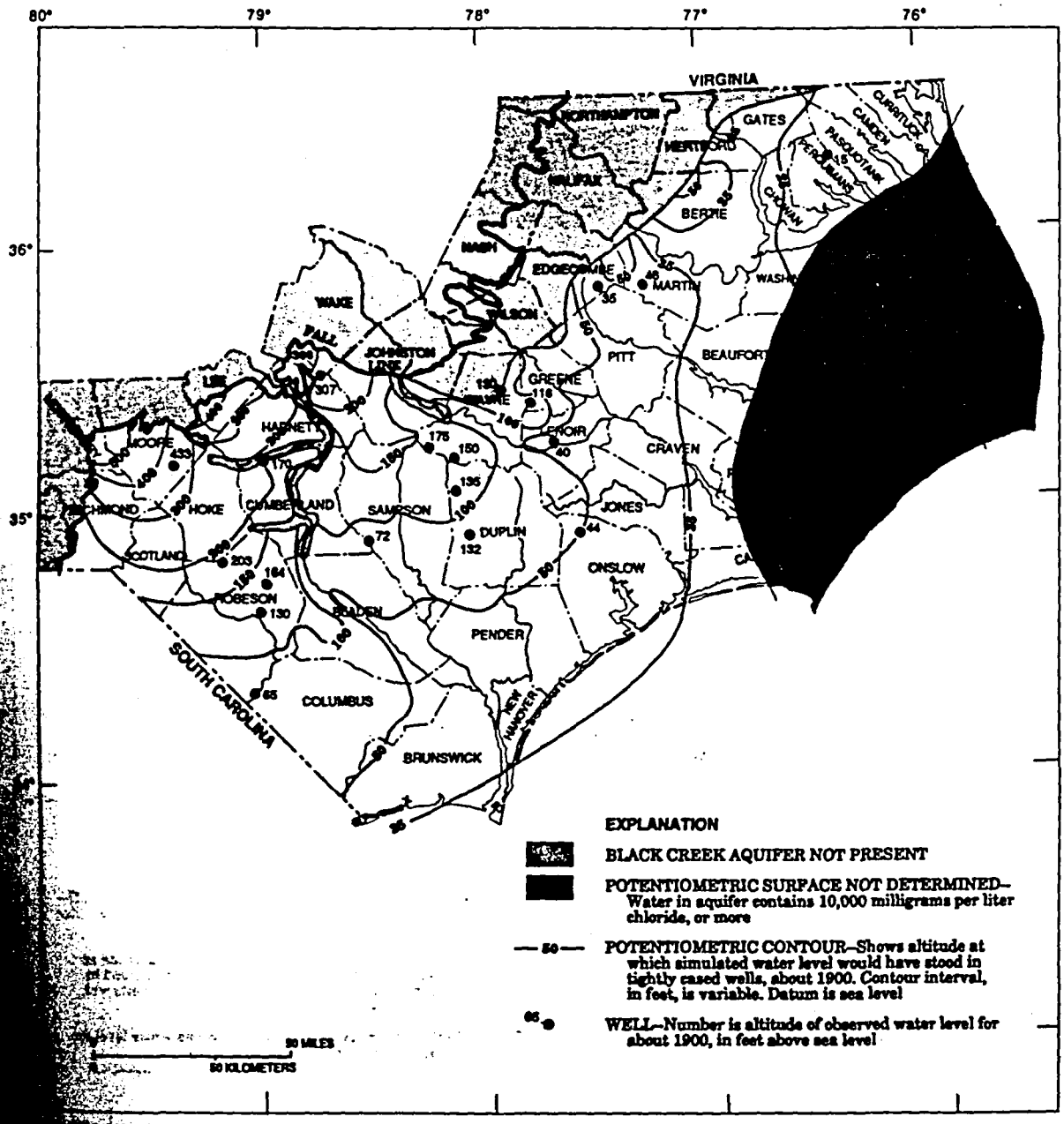


Figure 77.--Simulated prepumping (1900) potentiometric surface for the Black Creek aquifer (A4).

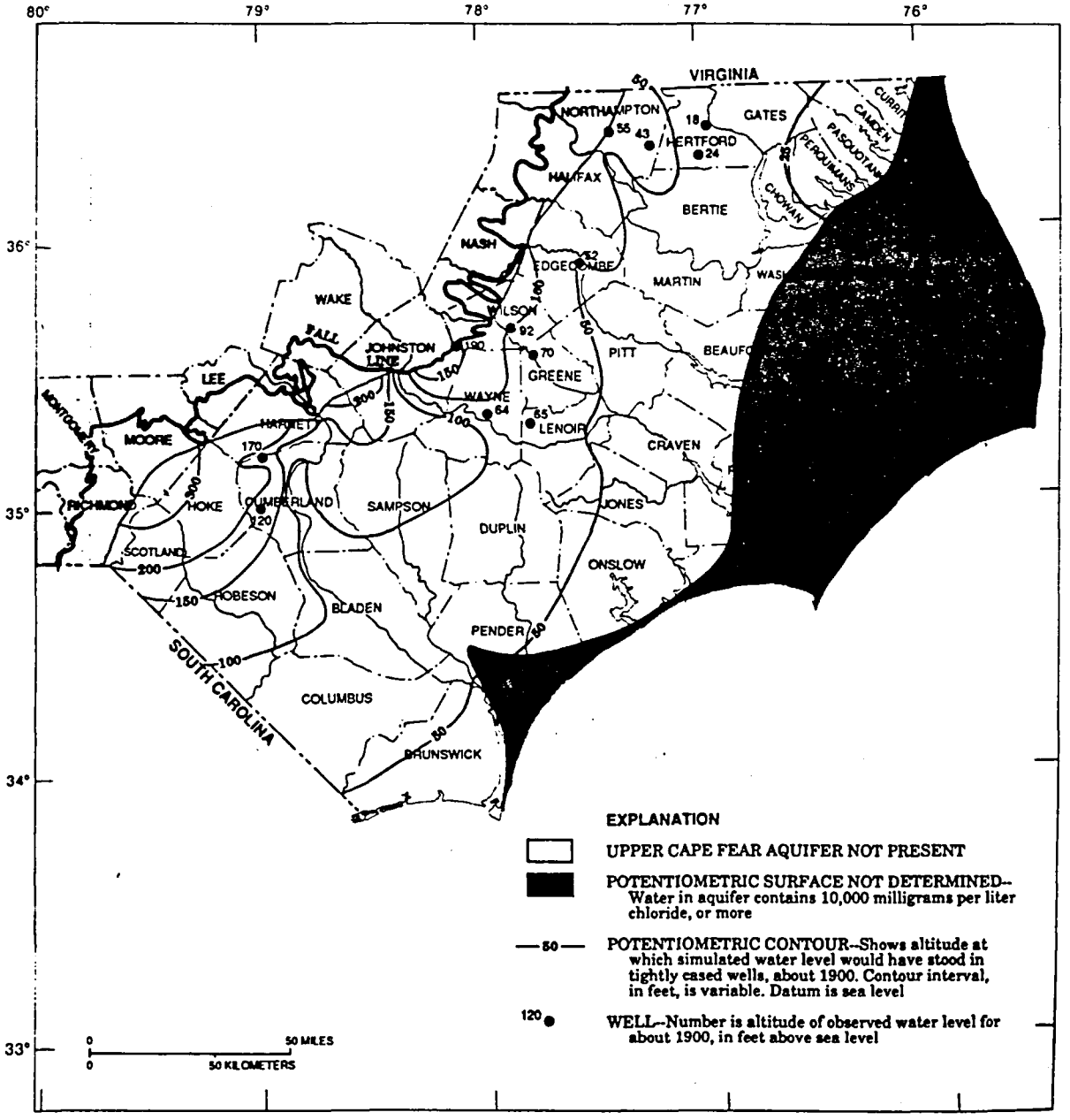


Figure 78.--Simulated prepumping (1900) potentiometric surface for the upper Cape Fear aquifer (A3).

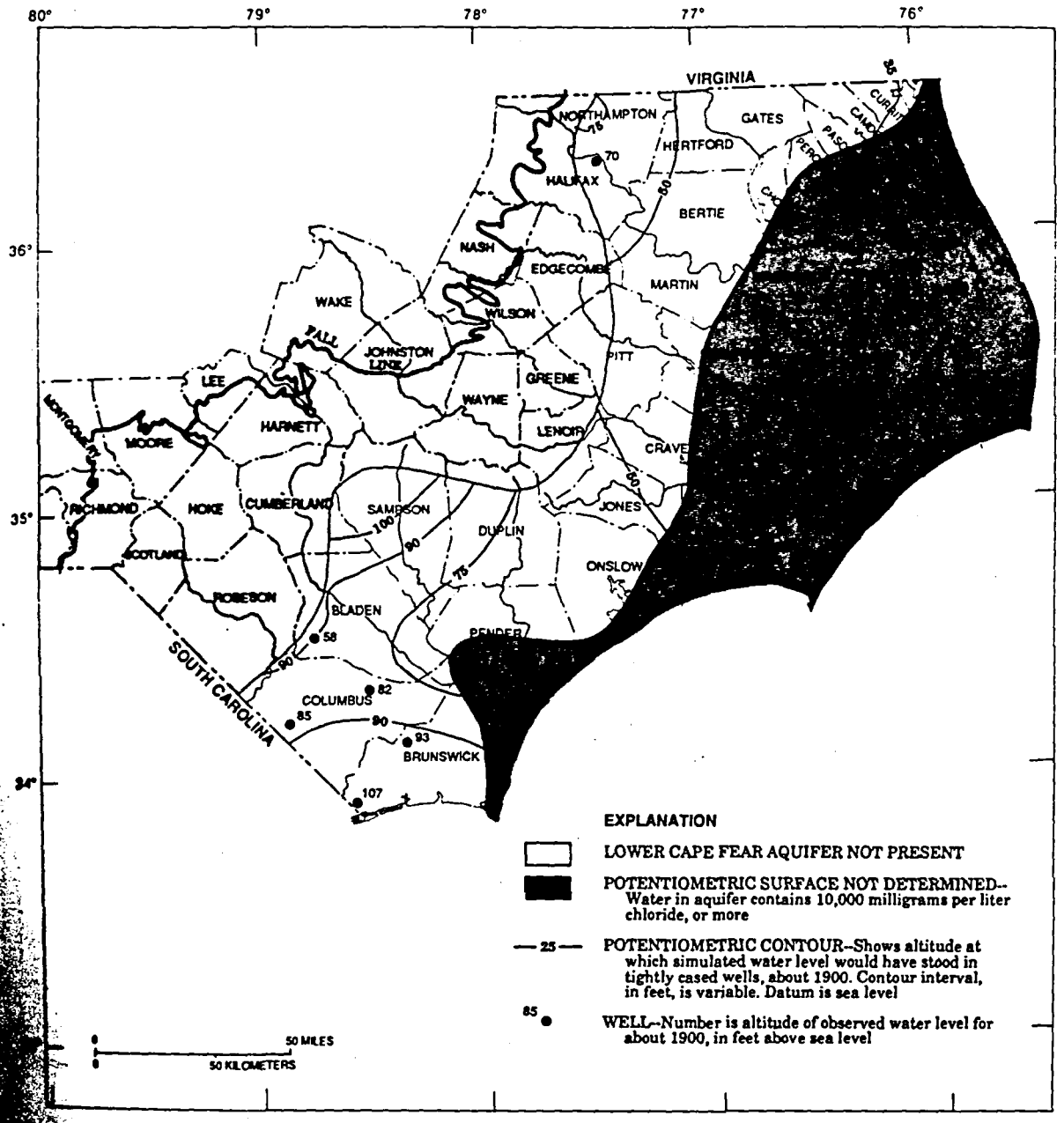


Figure 79.--Simulated prepumping (1900) potentiometric surface for the lower Cape Fear aquifer (A2).

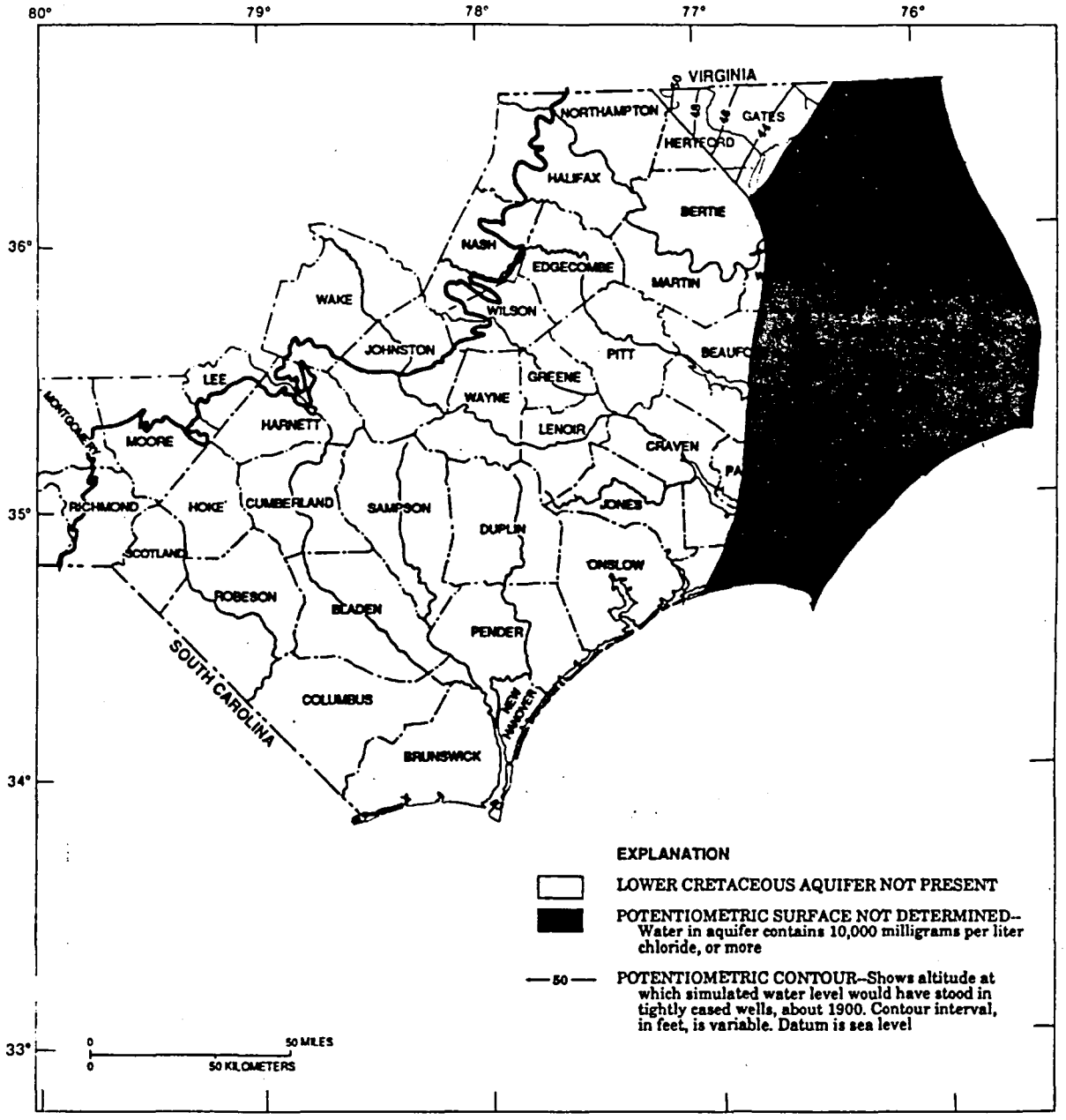


Figure 80.--Simulated prepumping (1900) potentiometric surface for the Lower Cretaceous aquifer (A1).

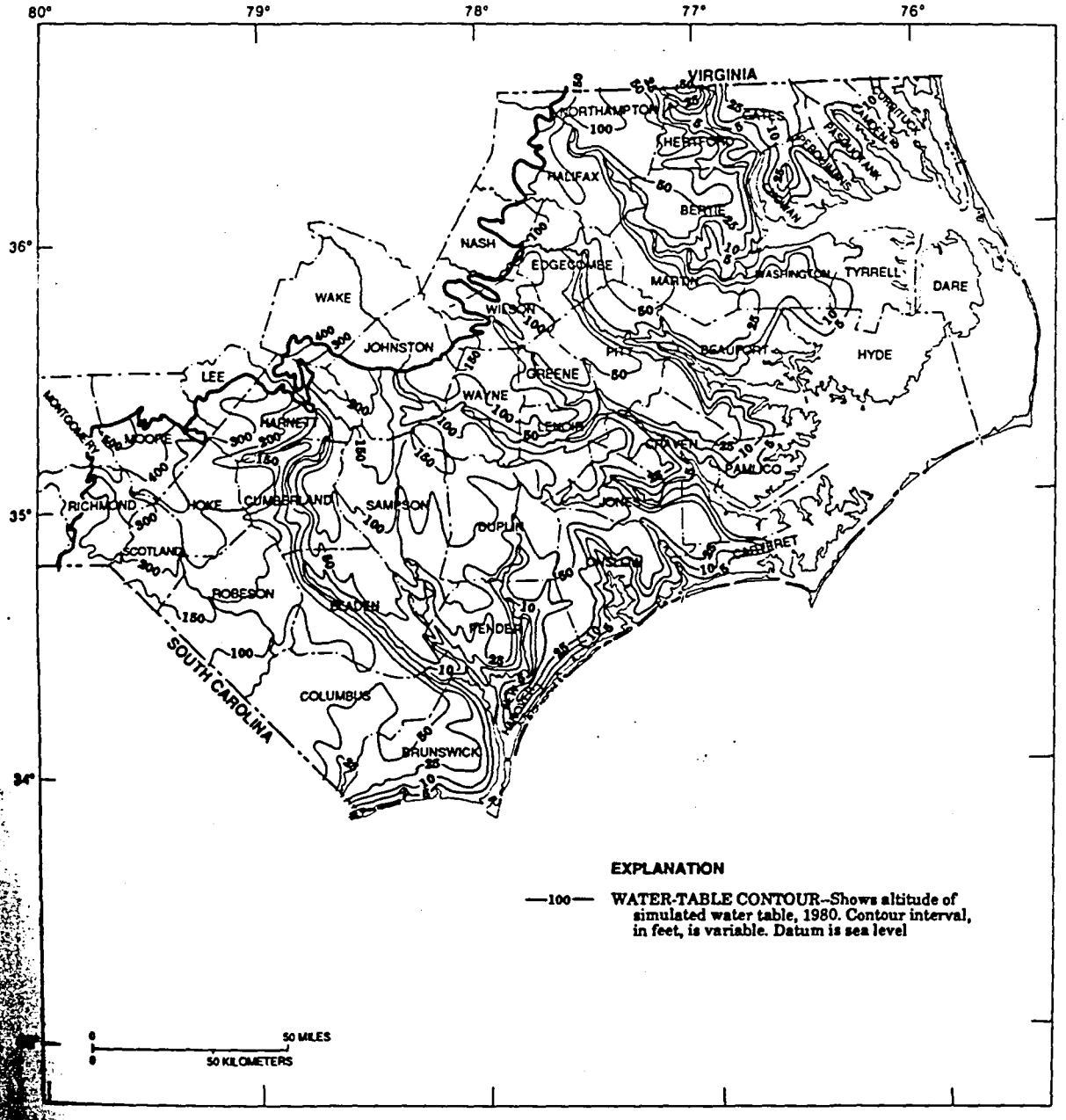


Figure 81.--Simulated 1980 water table for the surficial aquifer (A10).

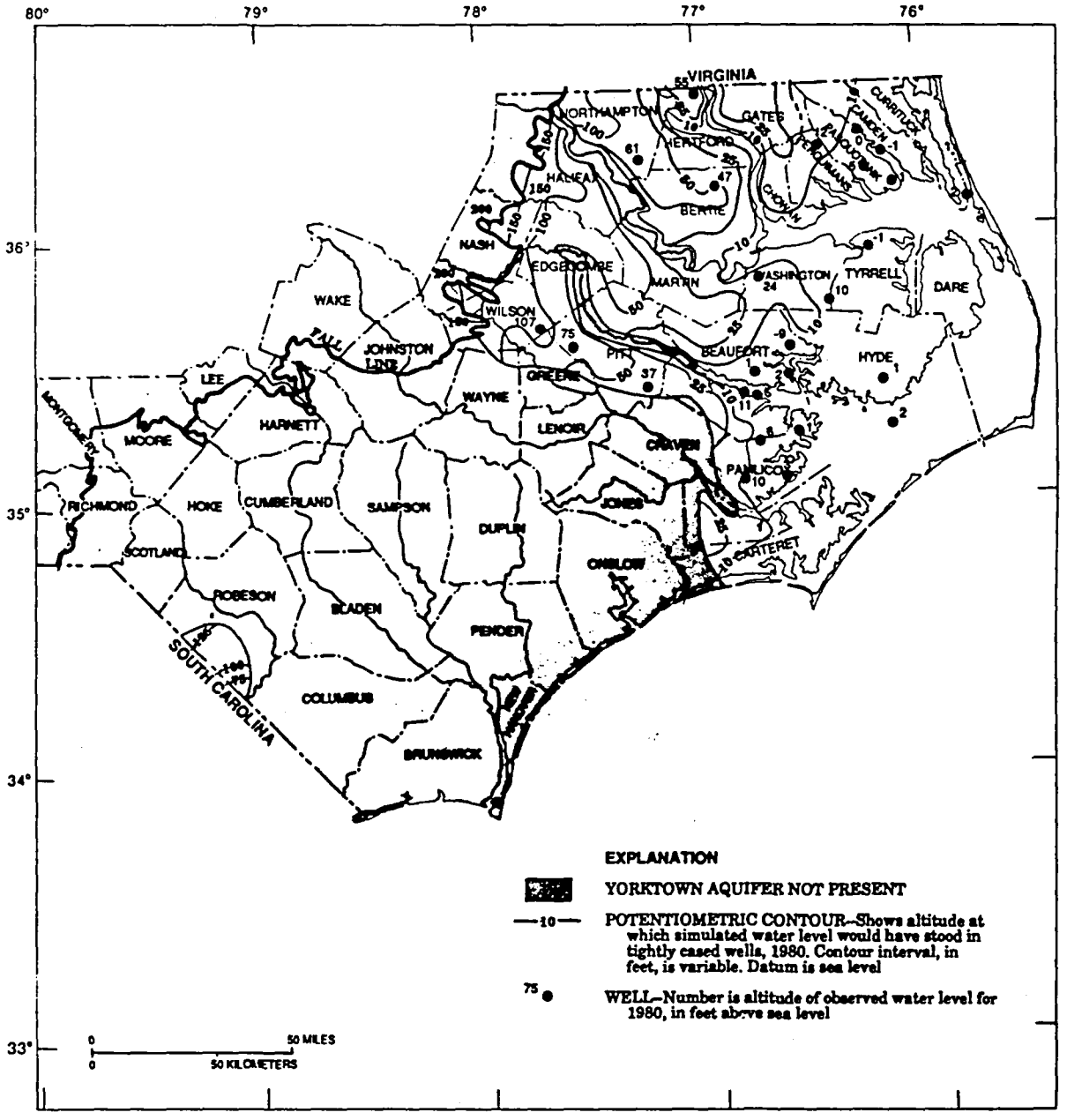


Figure 82.--Simulated 1980 potentiometric surface for the Yorktown aquifer (A9).

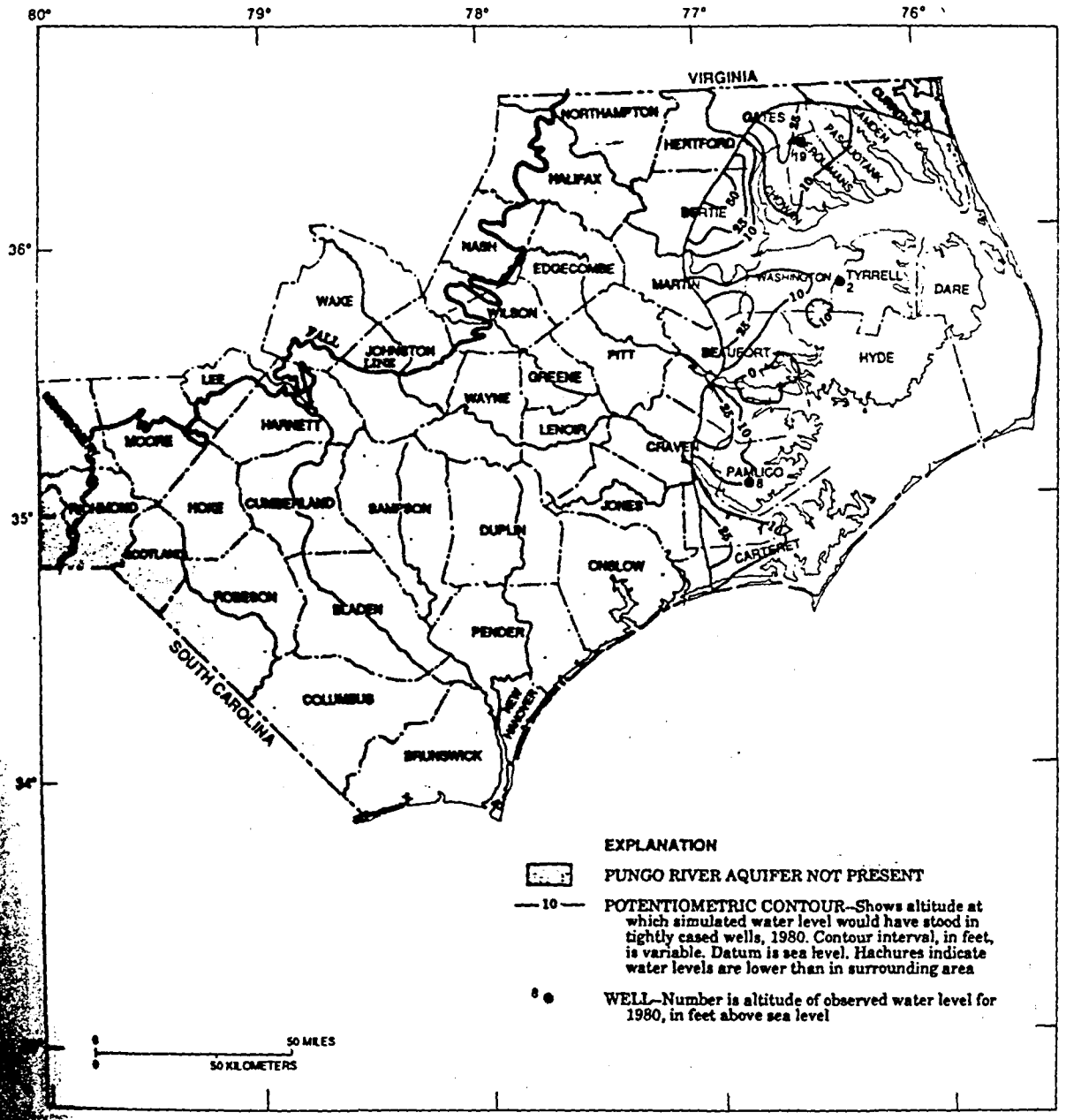


Figure 83.--Simulated 1980 potentiometric surface for the Pungo River aquifer (A8).

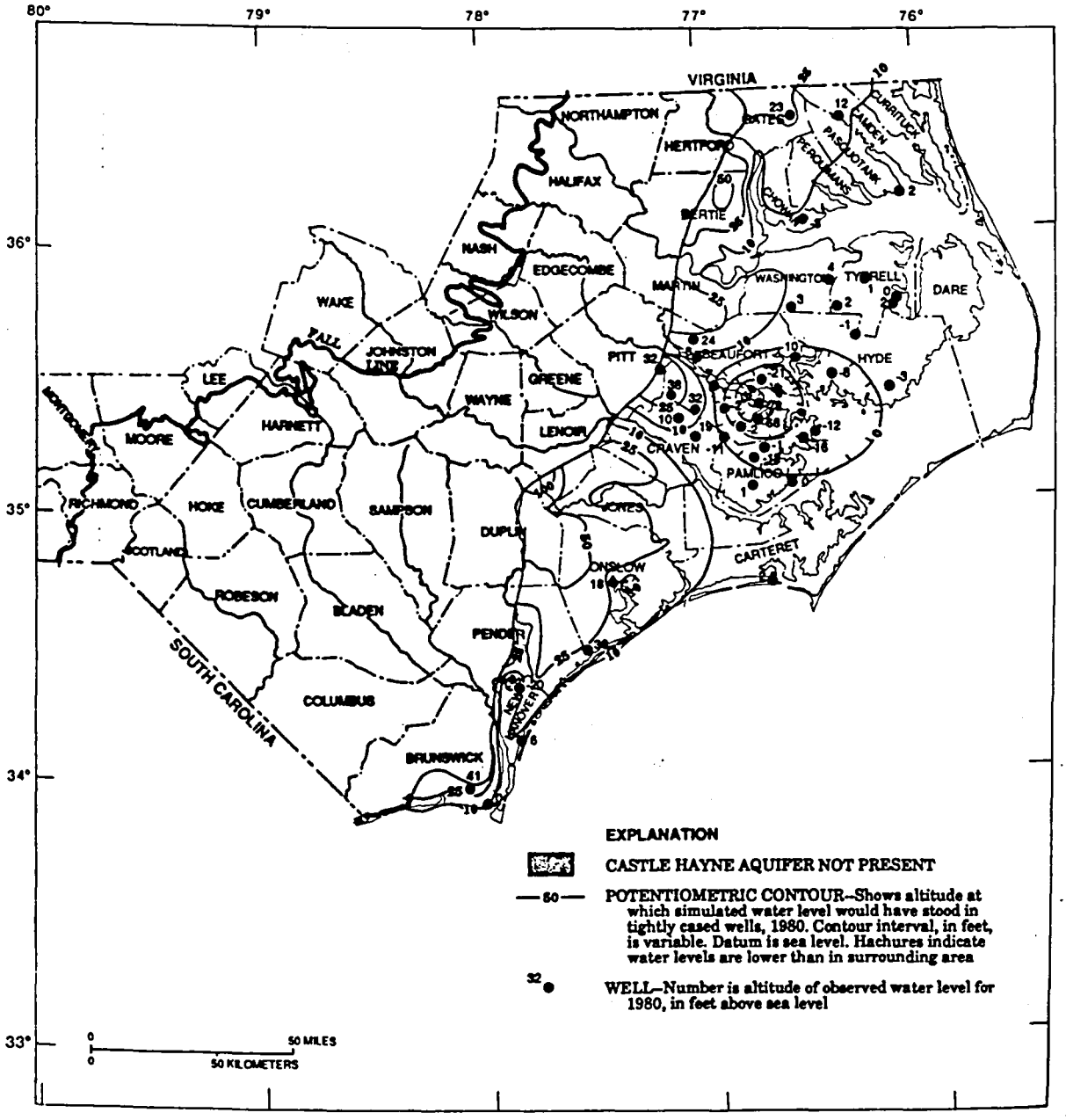
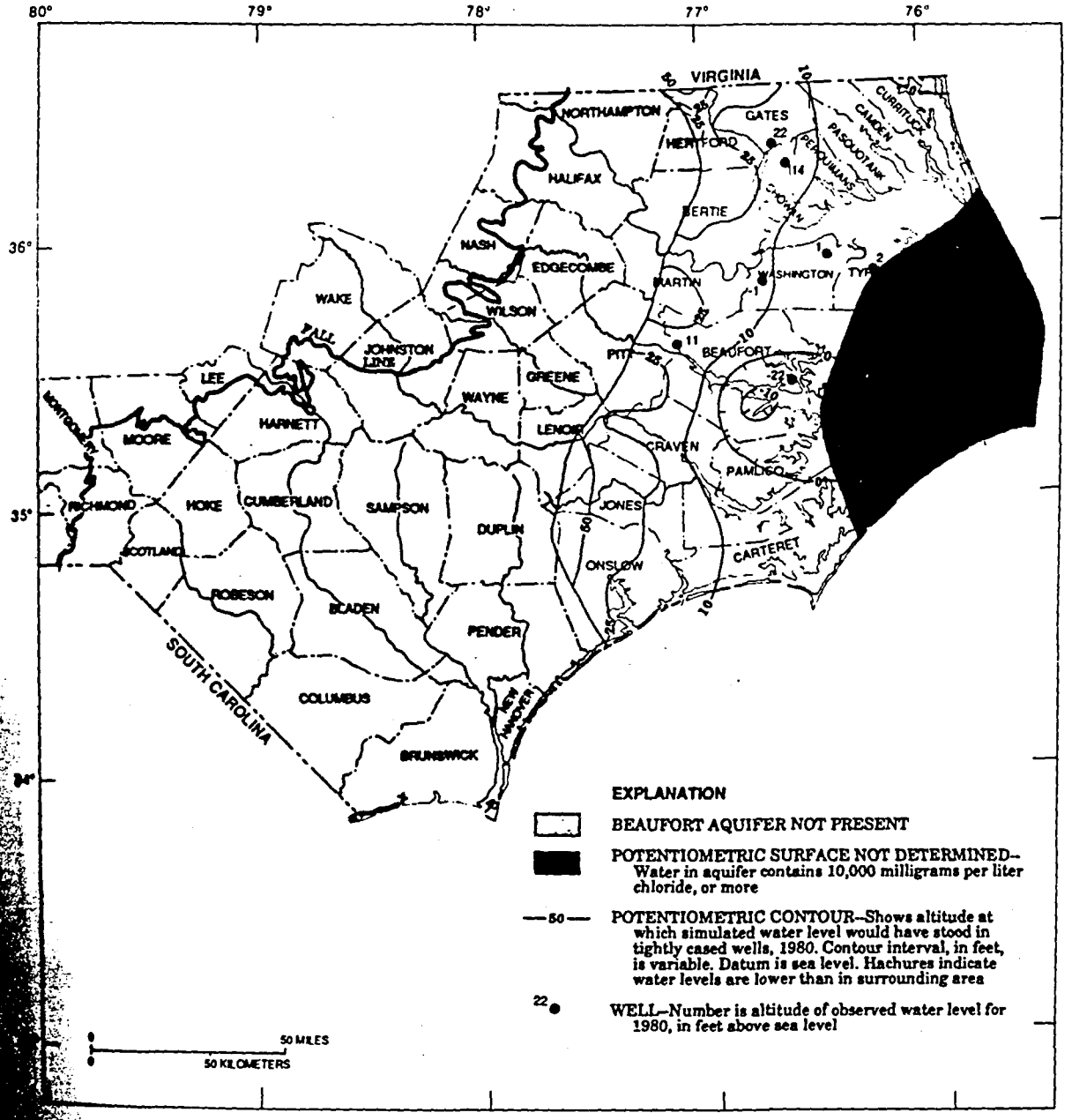


Figure 84.--Simulated 1980 potentiometric surface for the Castle Hayne aquifer (A7).



85.--Simulated 1980 potentiometric surface for the Beaufort aquifer (A6).

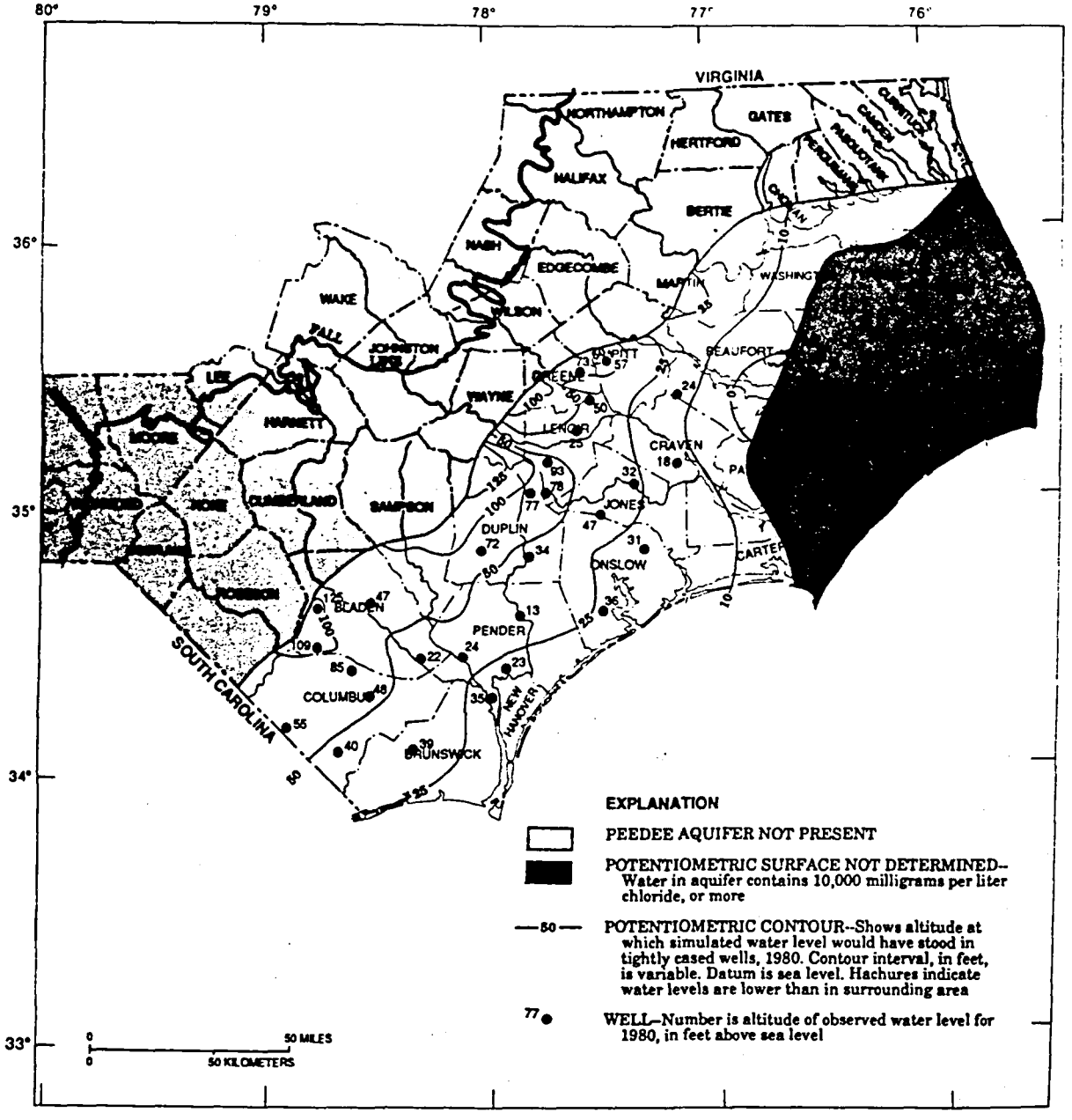


Figure 86.--Simulated 1980 potentiometric surface for the Peedee aquifer (A5).

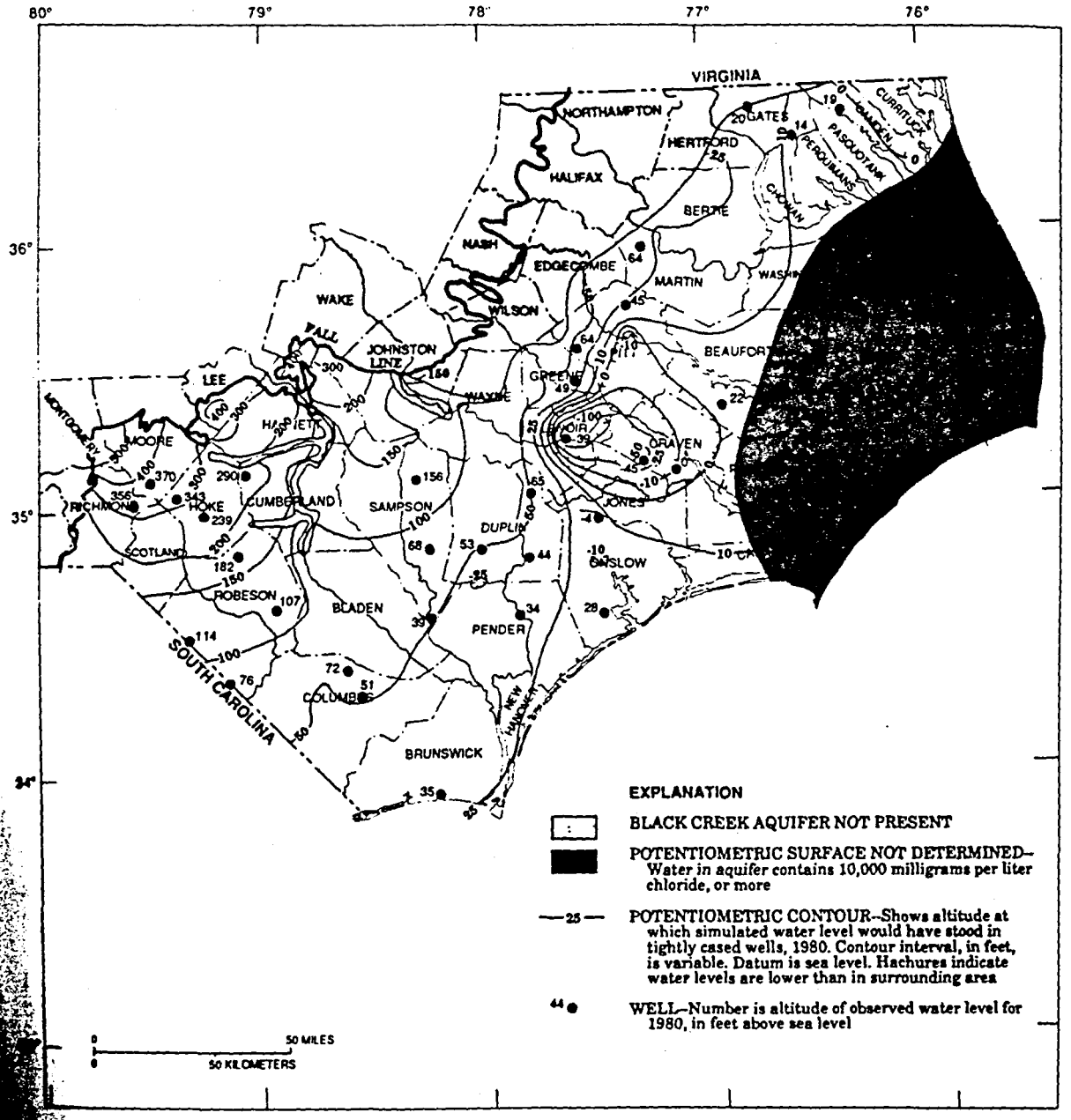


Figure 87.--Simulated 1980 potentiometric surface for the Black Creek aquifer (A4).

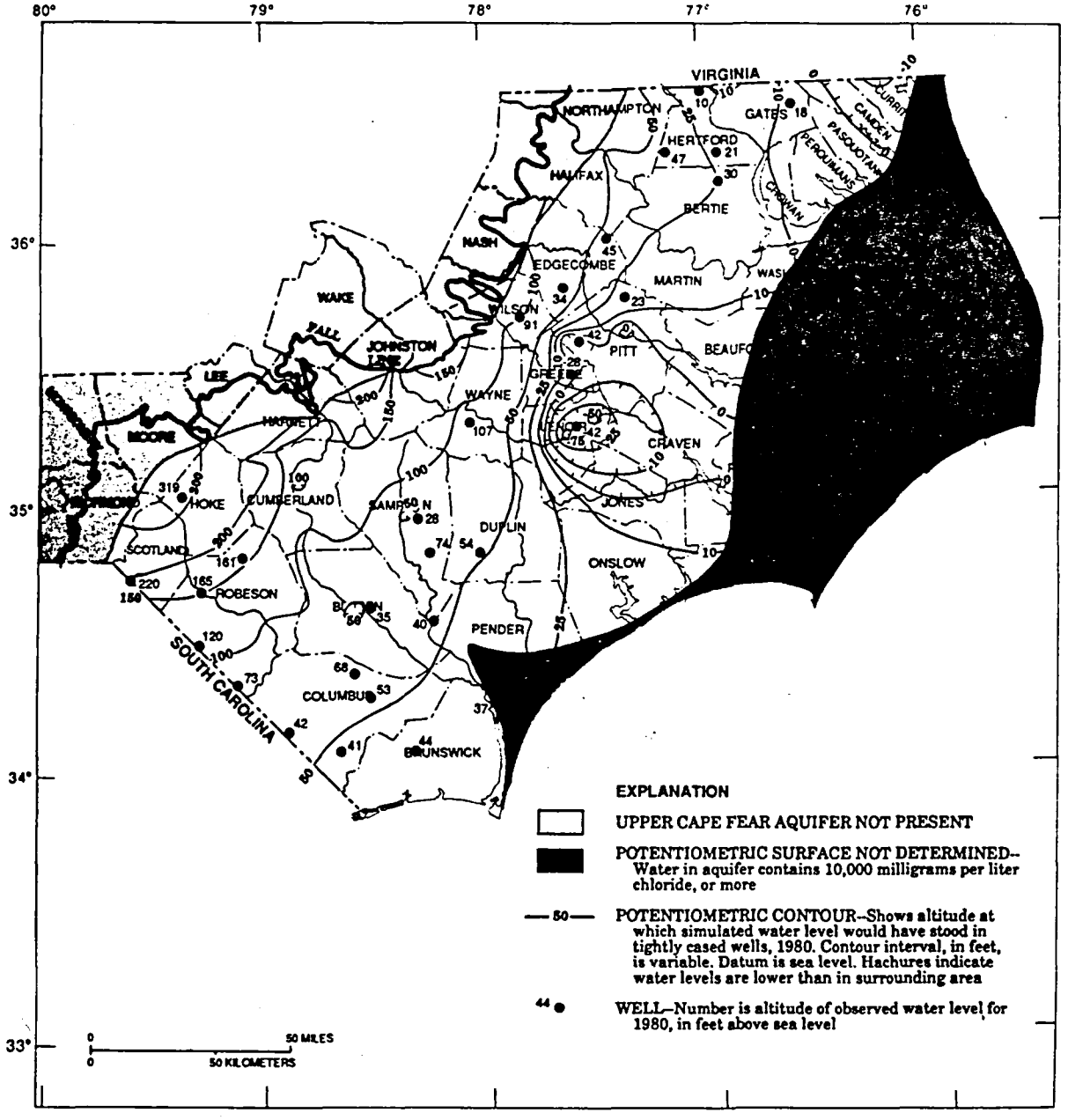


Figure 88.--Simulated 1980 potentiometric surface for the upper Cape Fear aquifer (A3).

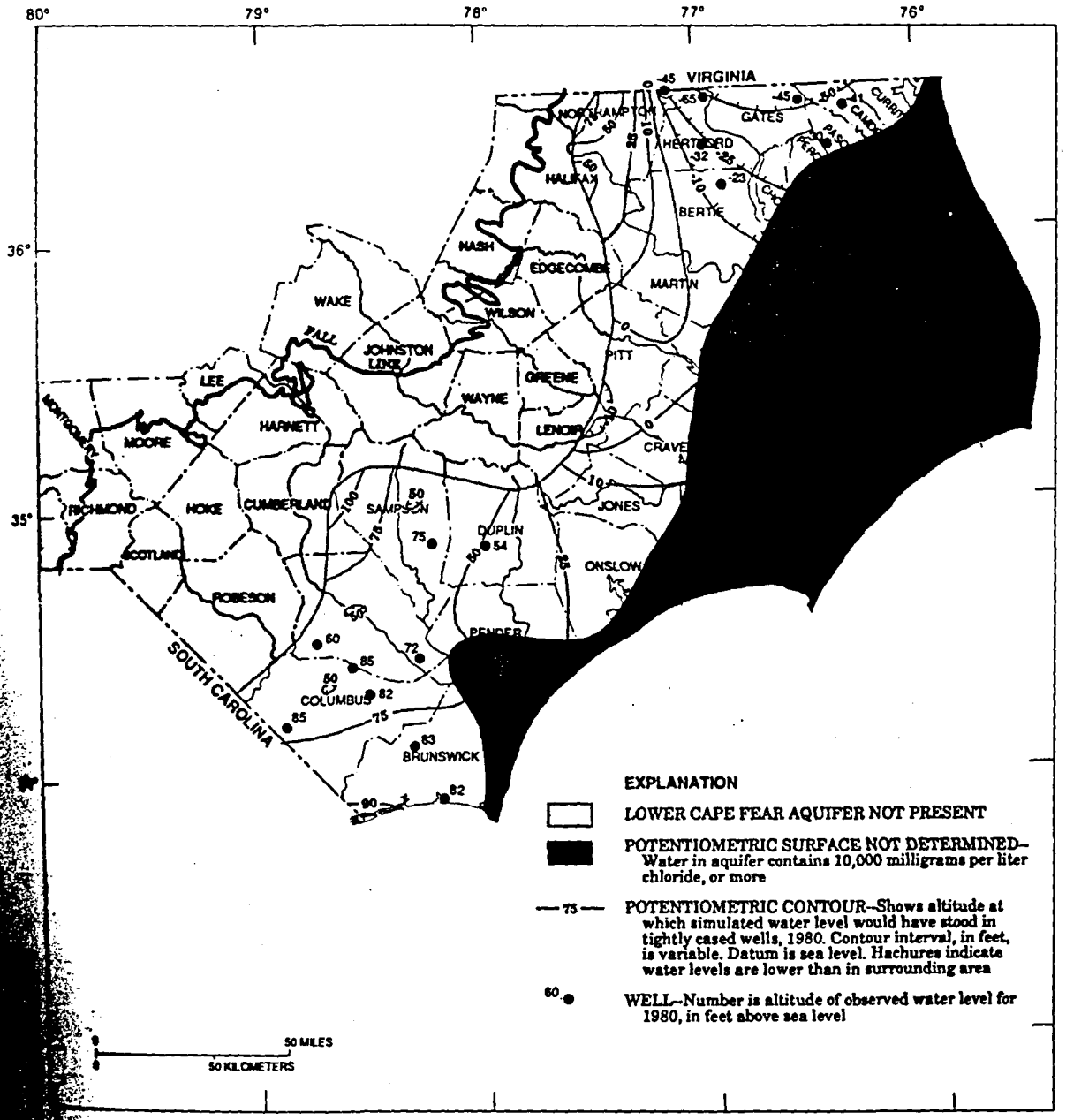


Figure 89.--Simulated 1980 potentiometric surface for the lower Cape Fear aquifer (A2).

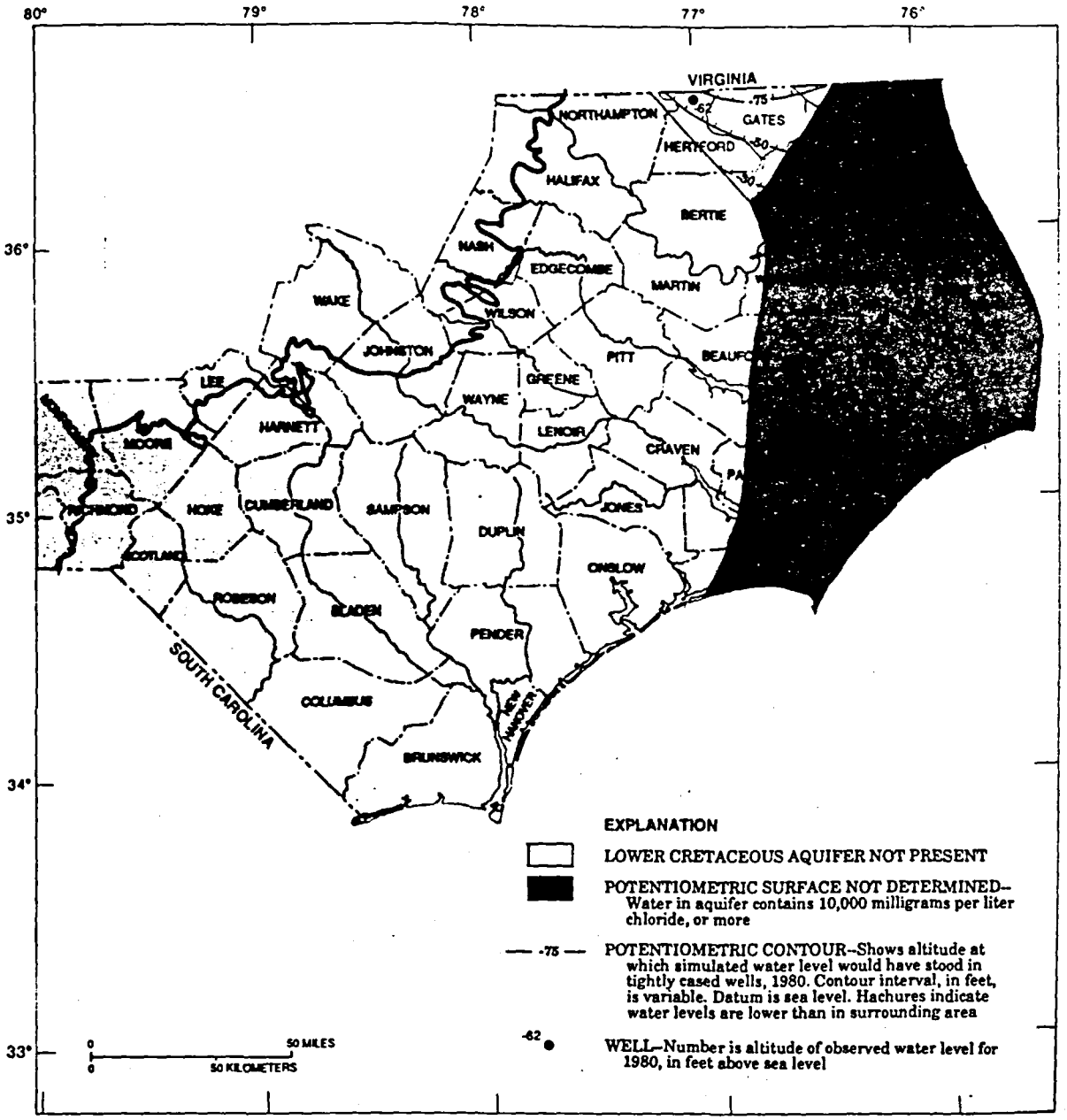


Figure 90.--Simulated 1980 potentiometric surface for the Lower Cretaceous aquifer (A1).

drawdowns of more than 135 ft and 90 ft occurred in parts of the Lower Cretaceous (A1) and lower Cape Fear (A2) aquifers, respectively, near the Virginia border. These drawdowns were due largely to pumpage at Franklin, Virginia (compare fig. 80 with 90 and fig. 79 with 89). Drawdowns of more than 60 ft, 125 ft, and 110 ft occurred in parts of the lower Cape Fear (A2), upper Cape Fear (A3), and Black Creek (A4) aquifers, respectively, in the central Coastal Plain in and around Greenville, Kinston, and Jacksonville, North Carolina. These drawdowns were due to several large withdrawals in the area; the large cone of depression associated with these withdrawals is most evident in figure 87.

Drawdowns of more than 30 ft and 60 ft occurred in parts of the Beaufort (A6) and Castle Hayne (A7) aquifers, respectively, in the Beaufort County area. Here, the drawdowns were caused in large part by withdrawals from the Castle Hayne aquifer (A7) in connection with open-pit phosphate mining operations and a chemical plant near Aurora (fig. 59); the cone of depression associated with these withdrawals is most evident in figure 84. A noteworthy aspect of the drawdown in the Beaufort aquifer (A6) is that no water was withdrawn directly from this aquifer at the mine and chemical plant. Withdrawals from the overlying Castle Hayne aquifer (A7) caused water to move upward through the Beaufort confining unit (CU6) in such quantities so as to create a large cone of depression in the Beaufort aquifer (A6) (fig. 85).

The simulated 1980 water level in the Castle Hayne aquifer (A7) near Aurora was slightly more than 50 ft below sea level, whereas measured water levels in some wells were greater than 100 ft below sea level in the withdrawal area. This difference in simulated and measured water levels results from the large block size used in the flow model. There, the simulated average water level over the 12.25 mi^2 block area was 50 ft or more higher than measured water levels in the center of the cone of depression.

The Peedee aquifer (A5) also showed a decline of about 15 ft between [illegible] and 1980 in the Aurora area (figs. 76 and 86). As with the Beaufort aquifer (A6), the Peedee aquifer has no major withdrawals in this area, and the water-level decline is similarly attributed to the effect of the large cone of depression in the overlying Castle Hayne aquifer (A7).

Although the calibrated flow model is not detailed enough for many management purposes, simulated potentiometric surfaces were generated (figs. 91 through 100) for the year 2000 (assuming a uniform 3-percent annual increase in pumpage for 1980-2000 at the 1980 pumpage sites) to assess the effect of future pumping on potentiometric surfaces. Actually, several major ground-water pumpages are not expected to increase at this rate during this period, notably at Franklin, Virginia, and at the phosphate-mining operations in Beaufort County, North Carolina. Thus, in these areas, the year 2000 simulations may not accurately reflect what is likely to occur.

Considerable areas of most aquifers exhibit drawdowns of less than 10 ft for the 1900-80 and 1980-2000 periods. Comparison of the water-table maps of 1900, 1980, and 2000 (figs. 71, 81, and 91) show little or no change in water levels in the surficial aquifer (A10). The same is true for the potentiometric surfaces of the Yorktown aquifer (A9) as seen in figures 72, 82, and 92. Except for the immediate vicinity of major withdrawals, potentiometric surfaces in the updip (western) parts of the Castle Hayne (A7), Beaufort (A6), Peedee (A5), Black Creek (A4), and upper Cape Fear (A3) aquifers declined 10 ft or less. The areas of little change for these confined aquifers are where each one is directly overlain by either the surficial aquifer (A10) or the Yorktown aquifer (A9). (Compare figures 73 through 78 and figures 83 through 88 and 93 through 98.)

By 1980, water levels in confined aquifers in the North Carolina Coastal Plain had not declined below the tops of the aquifers. When and if this happens, the aquifers will change from confined to unconfined conditions, and the aquifer storage coefficients will increase by several orders of magnitude (from about 10^{-4} to about 1×10^{-1}). Subsequent drawdowns will occur by dewatering rather than by expansion of the water and compaction of aquifer-/confining-unit sediments. Drawdowns will then proceed at a slower rate than under the previous confined conditions. Thus, model predictions of year 2000 water levels for such situations might tend to overestimate drawdowns regionally; however, locally they may underestimate drawdowns near the pumping centers.

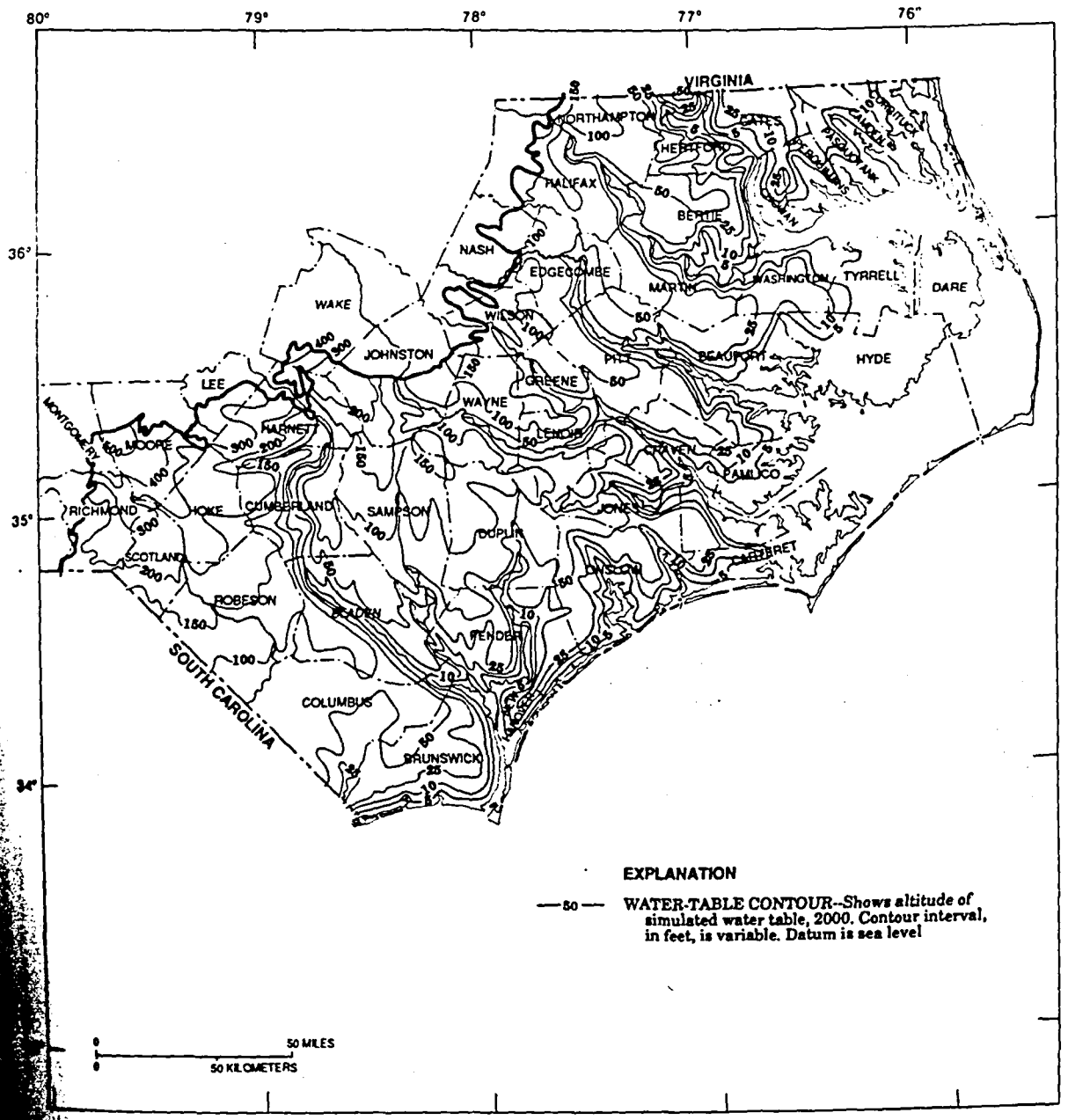


Figure 91.--Simulated year 2000 water table for the surficial aquifer (A10), assuming 3-percent annual increase in pumpage.

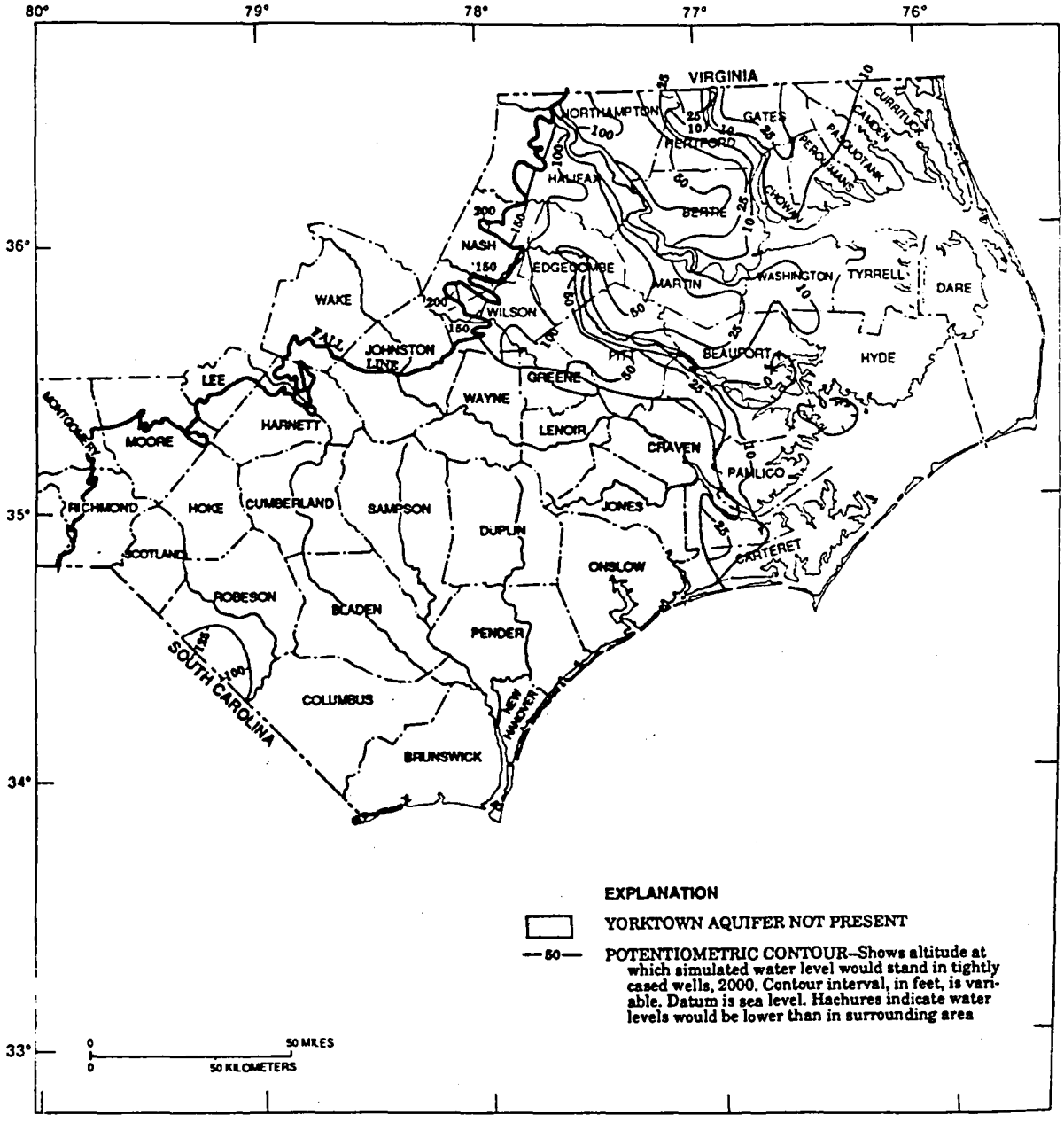


Figure 92.--Simulated year 2000 potentiometric surface for the Yorktown aquifer (A9), assuming 3-percent annual increase in pumpage.

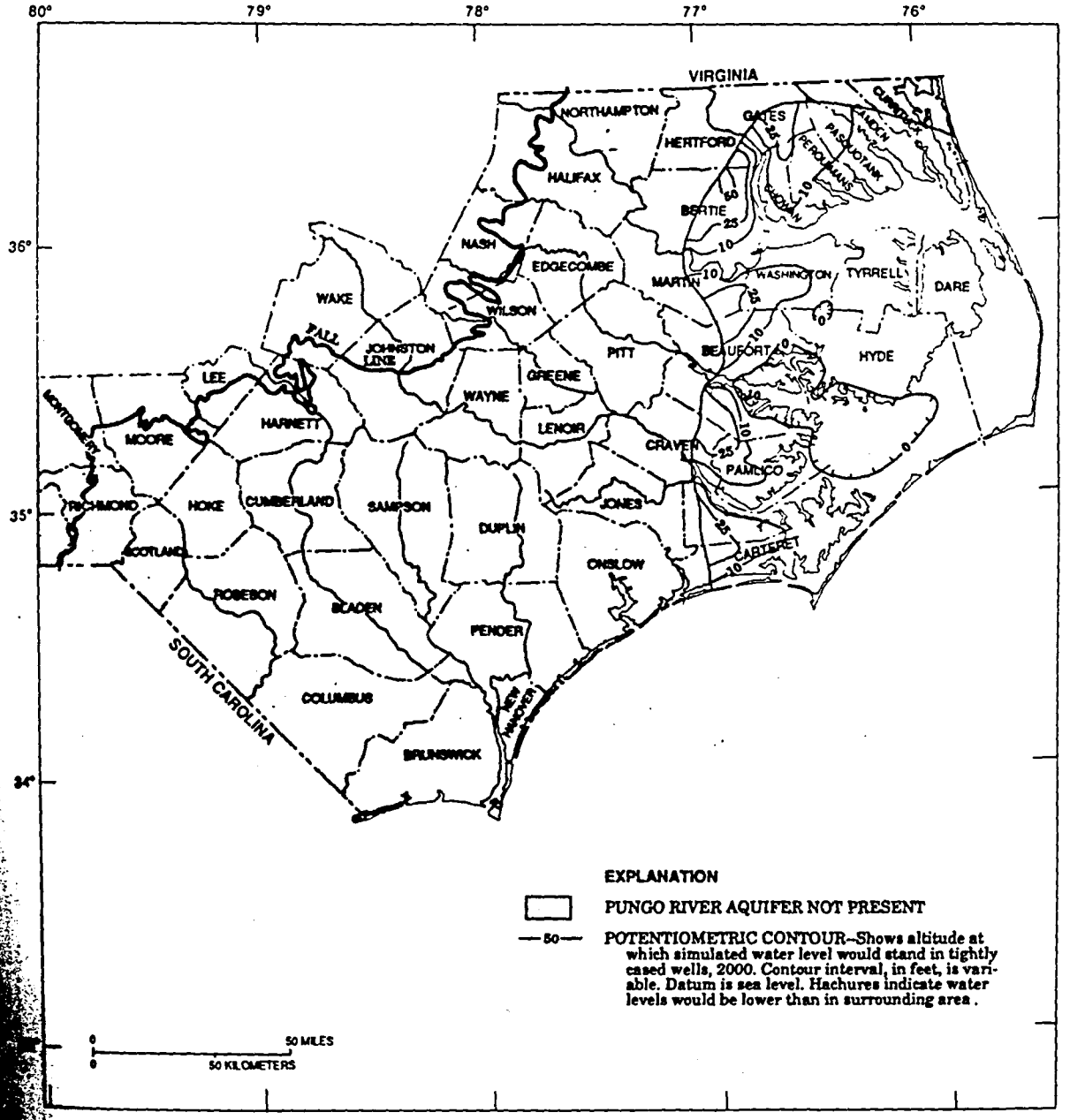


Figure 93.--Simulated year 2000 potentiometric surface for the Pungo River aquifer (A8), assuming 3-percent annual increase in pumpage.

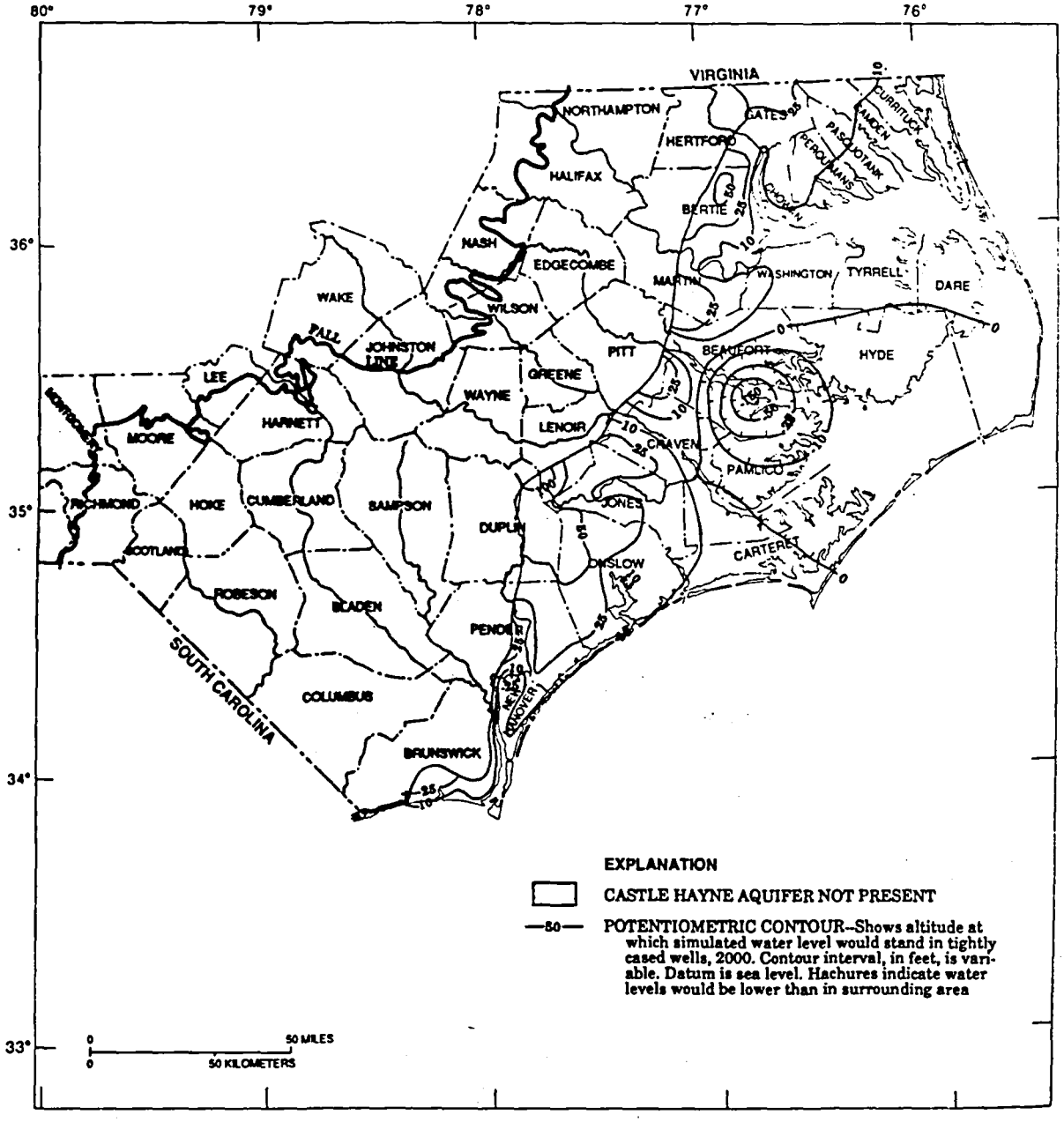


Figure 94.--Simulated year 2000 potentiometric surface for the Castle Hayne aquifer (A7), assuming 3-percent annual increase in pumpage.

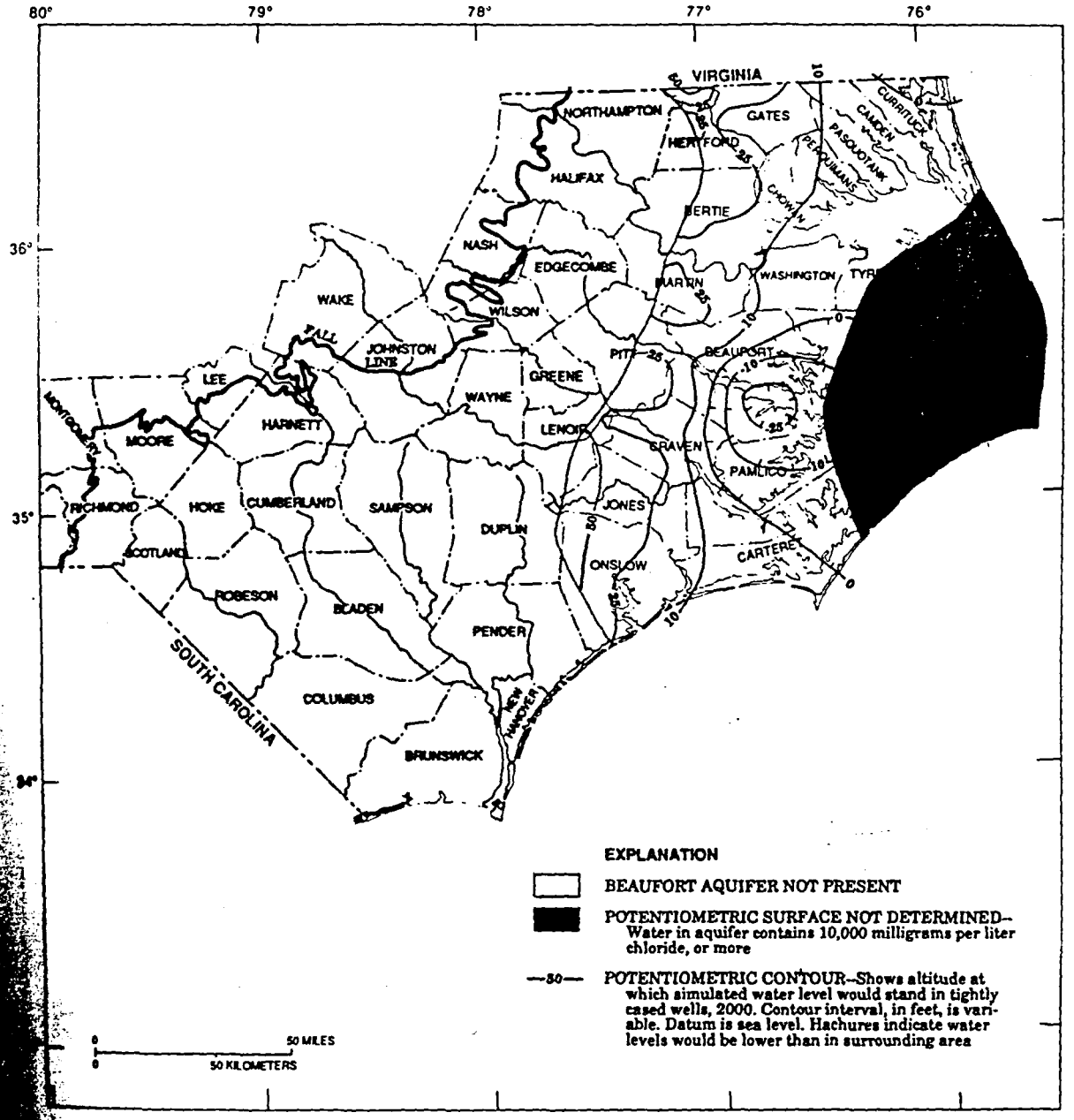


Figure 95.--Simulated year 2000 potentiometric surface for the Beaufort aquifer (A6), assuming 3-percent annual increase in pumpage.

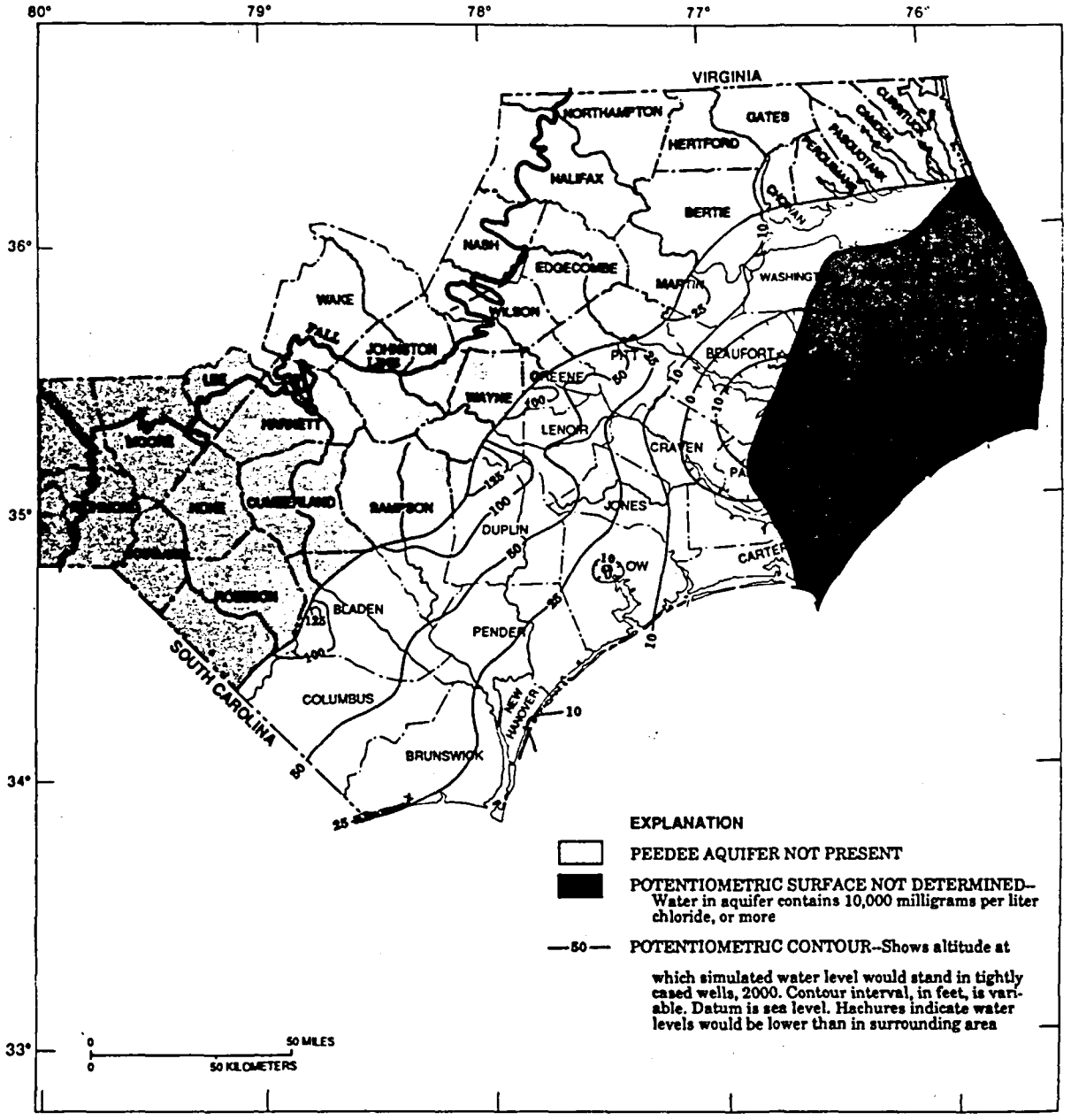


Figure 96.--Simulated year 2000 potentiometric surface for the Peedee aquifer (A5), assuming 3-percent annual increase in pumpage.

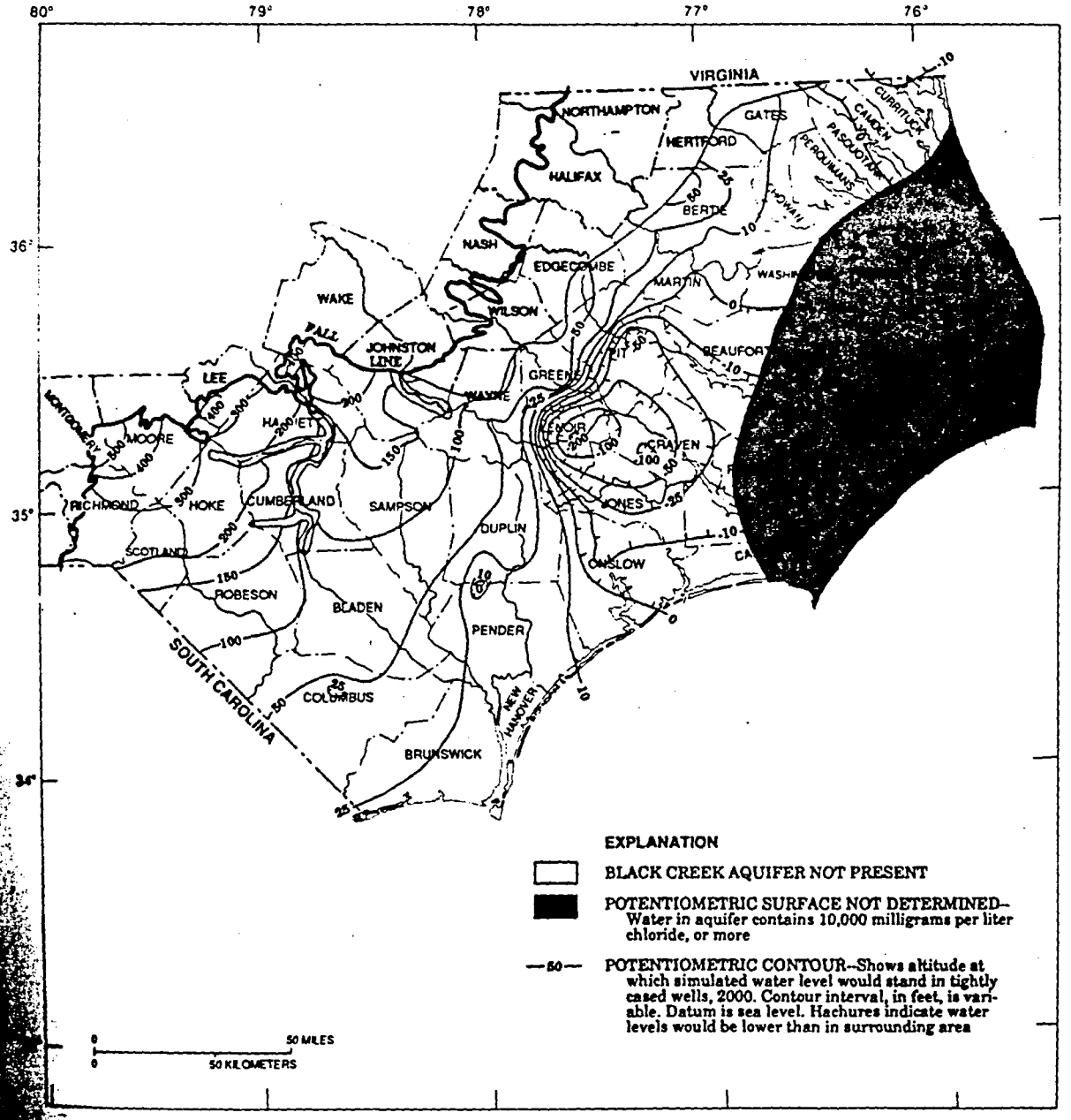


Figure 97.--Simulated year 2000 potentiometric surface for the Black Creek aquifer (A4), assuming 3-percent annual increase in pumpage.

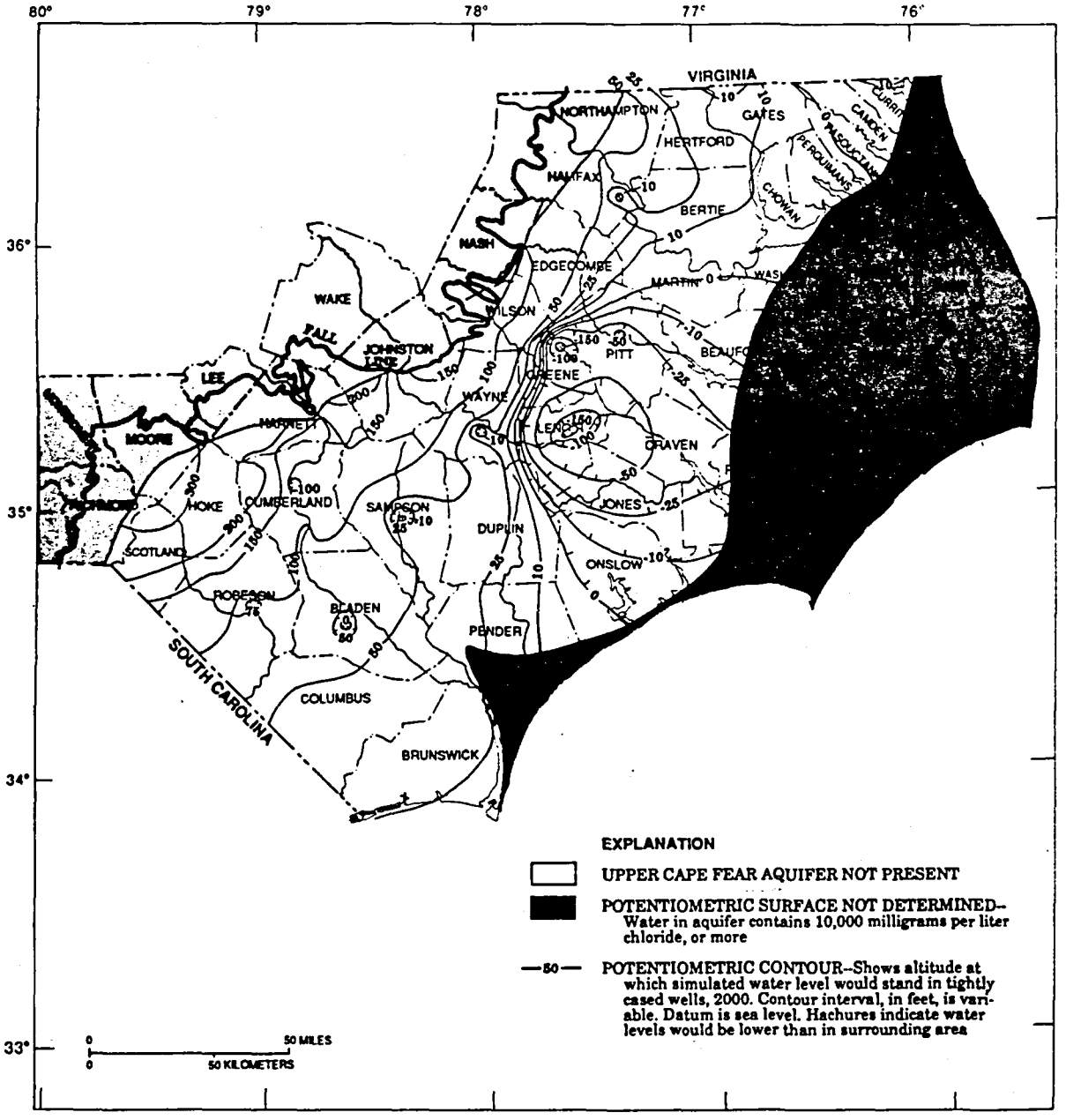


Figure 98.--Simulated year 2000 potentiometric surface for the upper Cape Fear aquifer (A3), assuming 3-percent annual increase in pumpage.

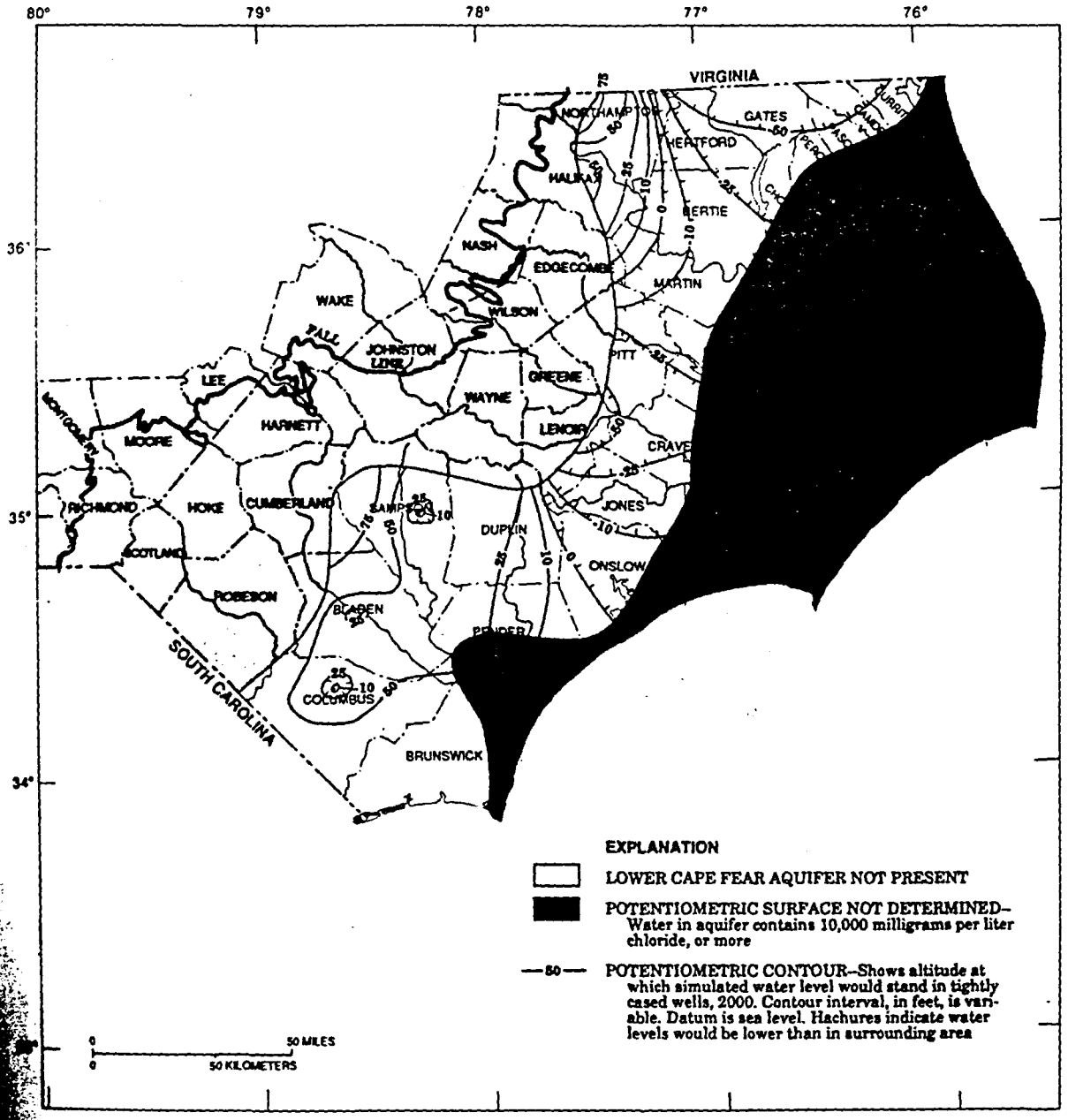


Figure 99.--Simulated year 2000 potentiometric surface for the lower Cape Fear aquifer (A2), assuming 3-percent annual increase in pumpage.

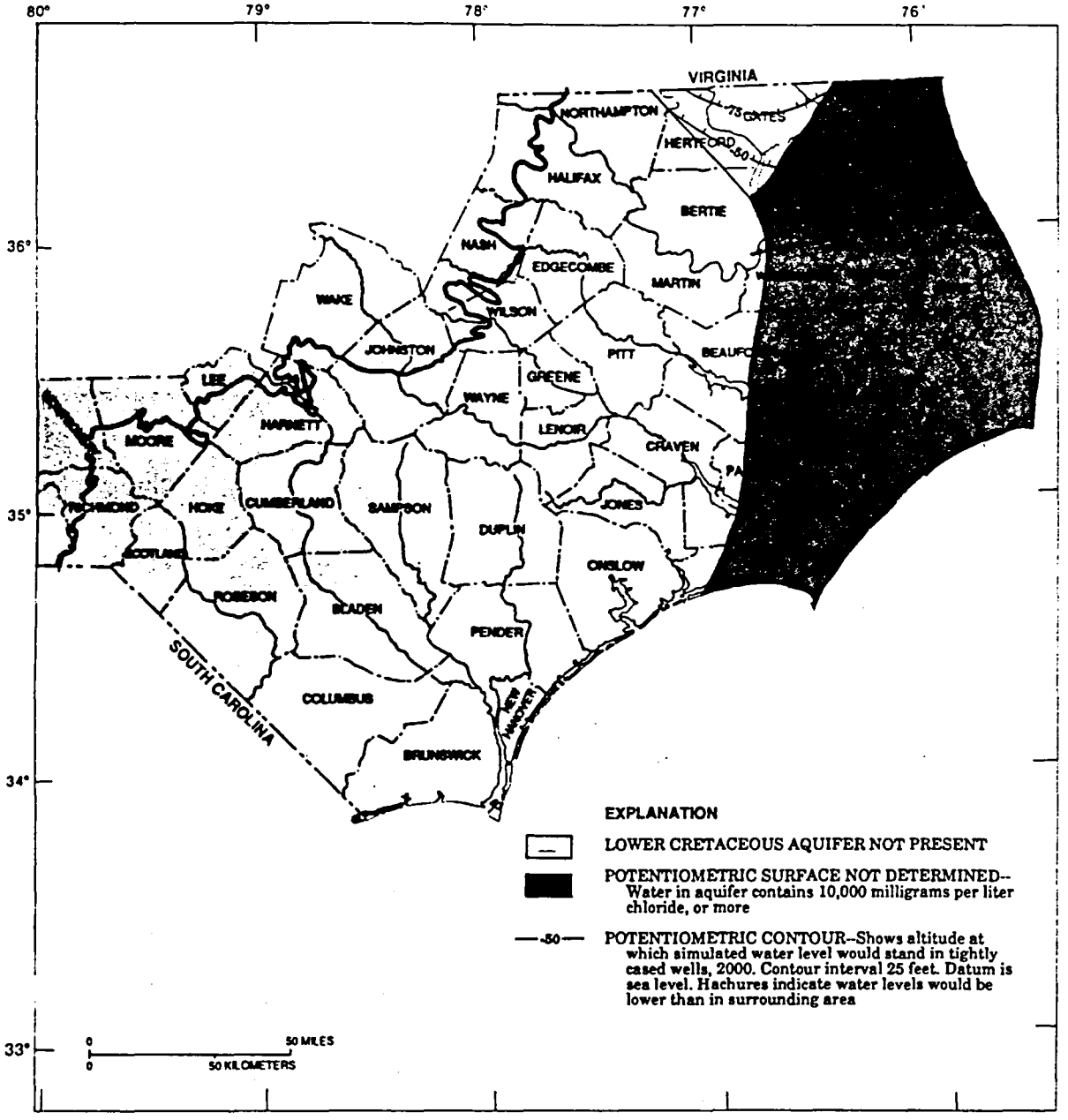


Figure 100.--Simulated year 2000 potentiometric surface for the Lower Cretaceous aquifer (A1), assuming 3-percent annual increase in pumpage.

Vertical Flow

As a generalization, the downward vertical movement of ground-water recharge to confined aquifers under natural conditions occurs mainly in interstream areas, and ground-water discharge upward from the confined aquifer system occurs mainly in stream valleys and in downdip (coastward) areas. This general pattern of recharge and discharge has been significantly altered in several areas of the North Carolina Coastal Plain where pumping from several of the aquifers has reduced the hydraulic head in these aquifers over large areas and has thus disturbed the prepumping head relations that existed between the aquifers. When those head relations are changed, the potential for water to move from one aquifer to another through the intervening confining unit(s) is changed and often reversed. The changes in flow direction due to pumping is evident from a comparison of prepumping conditions of 1900 in figures 101-109 to those of 1980 in figures 110-118.

In the northeast North Carolina Coastal Plain, prepumping vertical ground-water flow through the Black Creek (CU4), upper Cape Fear (CU3), lower Cape Fear (CU2), and Lower Cretaceous (CU1) confining units (figs. 106-109) was upward in many parts of the area. By 1980, vertical flow gradients had been reversed across large parts of these confining units (figs. 115-118). Vertical flow by 1980 was downward in response to large pumpages from the Lower Cretaceous (A1) and lower Cape Fear (A2) aquifers in Franklin, Virginia.

Extensive pumping from the Black Creek (A4), and upper Cape Fear (A3) aquifers in the central North Carolina Coastal Plain area has resulted in reversal of flow from upward to downward through the Peedee (CU5), Black Creek (CU4), and upper Cape Fear (CU3) confining units (figs. 105 to 107 and 114 to 116). However, flow through the upper Cape Fear confining unit in the area between Kinston and New Bern is still upward in response to pumping from the overlying Black Creek aquifer (A4), which is pumped more heavily than the upper Cape Fear aquifer (A3). A large area of the Black Creek confining unit (CU4) in the southern North Carolina Coastal Plain has experienced a change in vertical flow from upward to downward in response to moderate but widespread pumping (figs. 106 and 115).

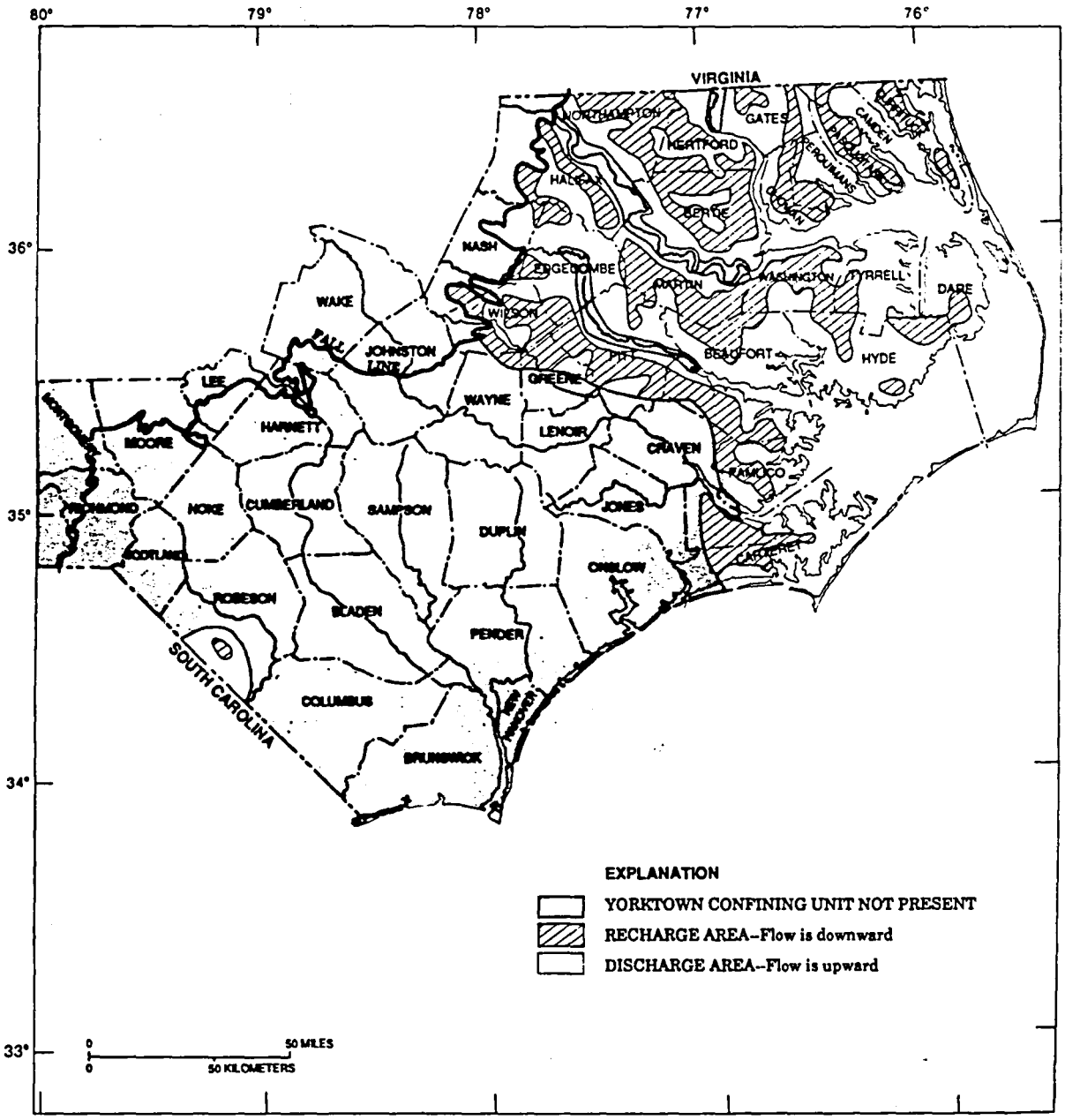


Figure 101.--Net vertical flow of water through the Yorktown confining unit (CU9) simulated for predevelopment (1900) conditions.

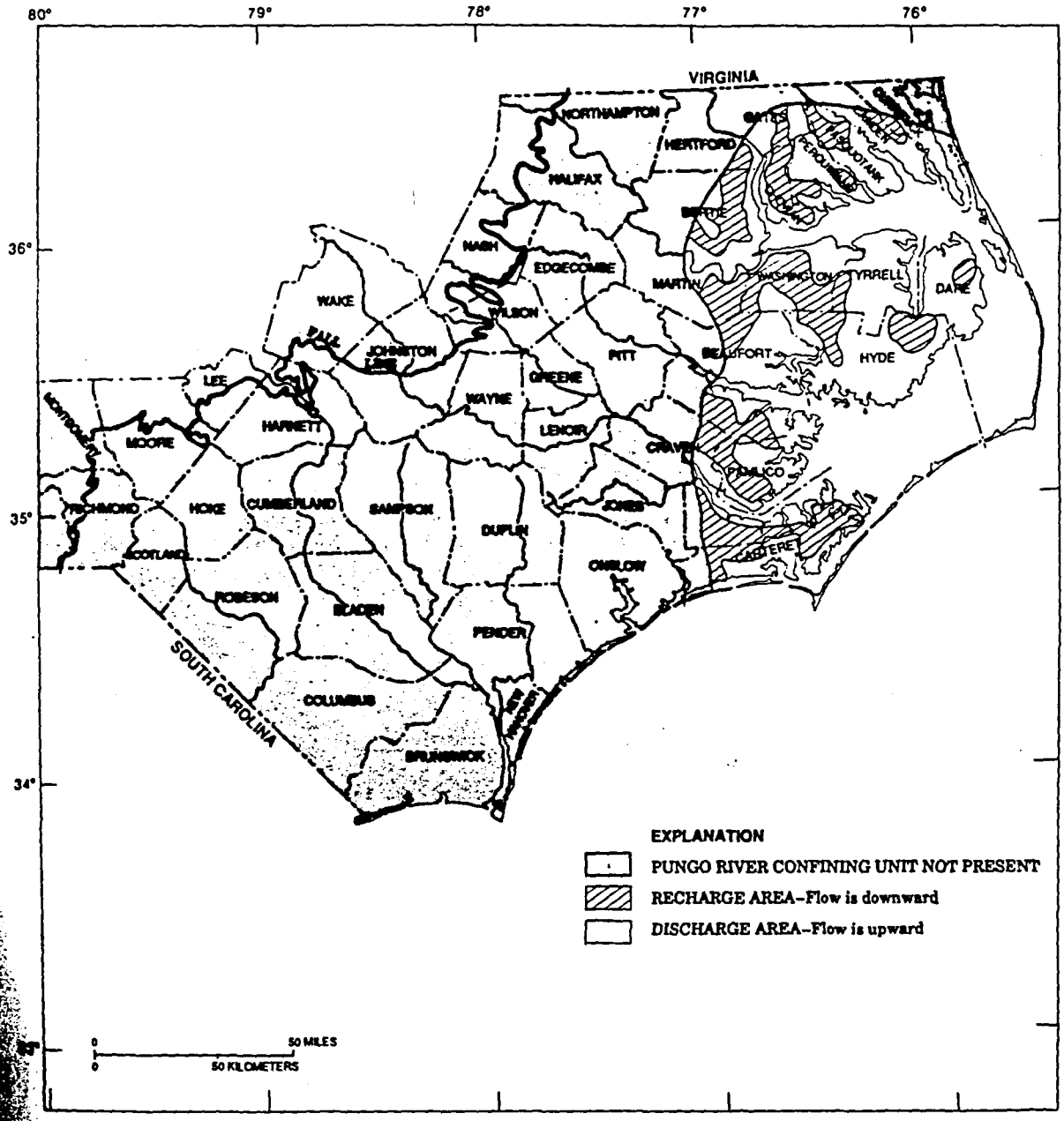


Figure 102.--Net vertical flow of water through the Pungo River confining unit (CU8) simulated for predevelopment (1900) conditions.

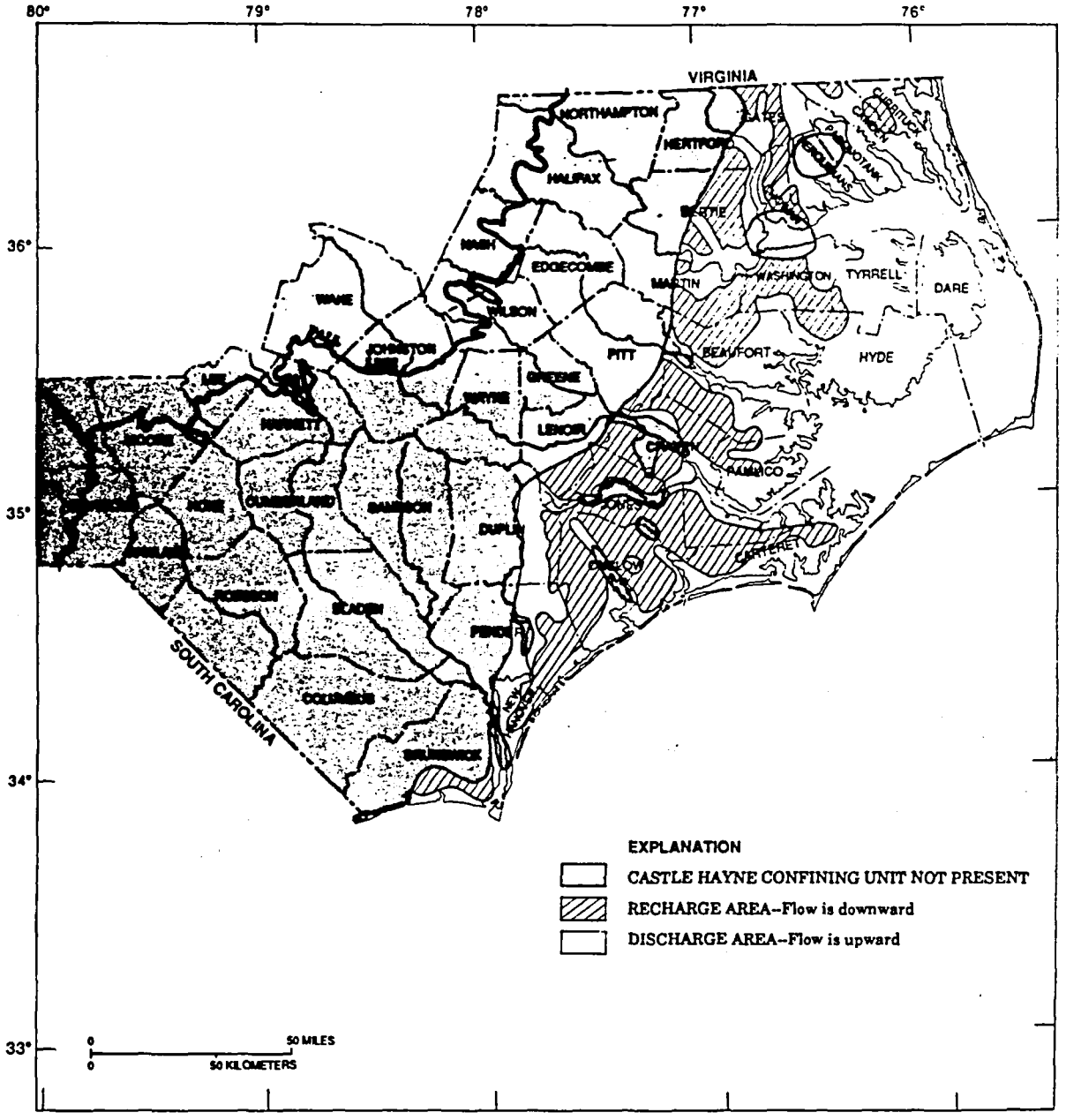


Figure 103.--Net vertical flow of water through the Castle Hayne confining unit (CU7) simulated for predevelopment (1900) conditions.

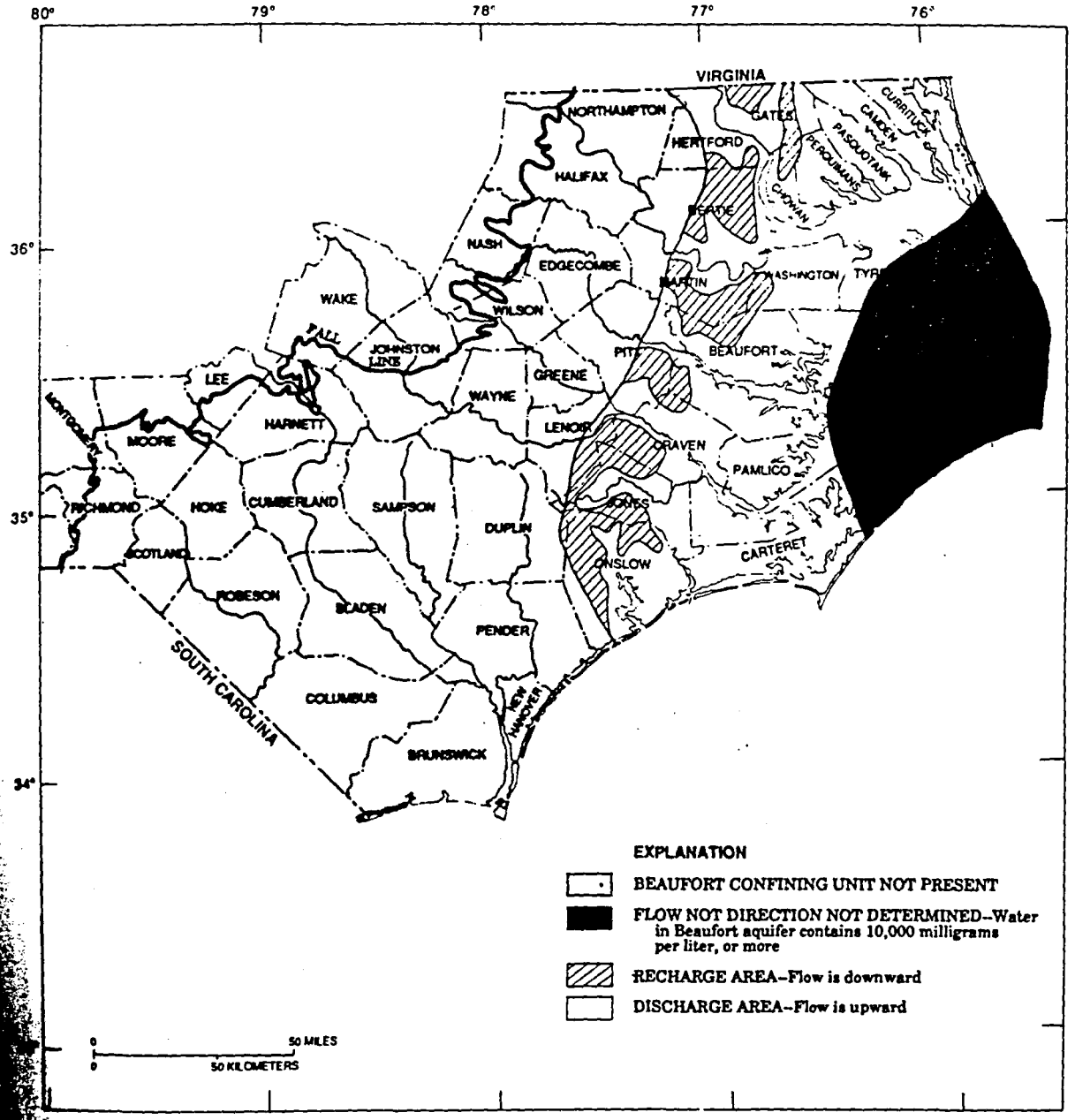


Figure 104.--Net vertical flow of water through the Beaufort confining unit (CU6) simulated for predevelopment (1900) conditions.

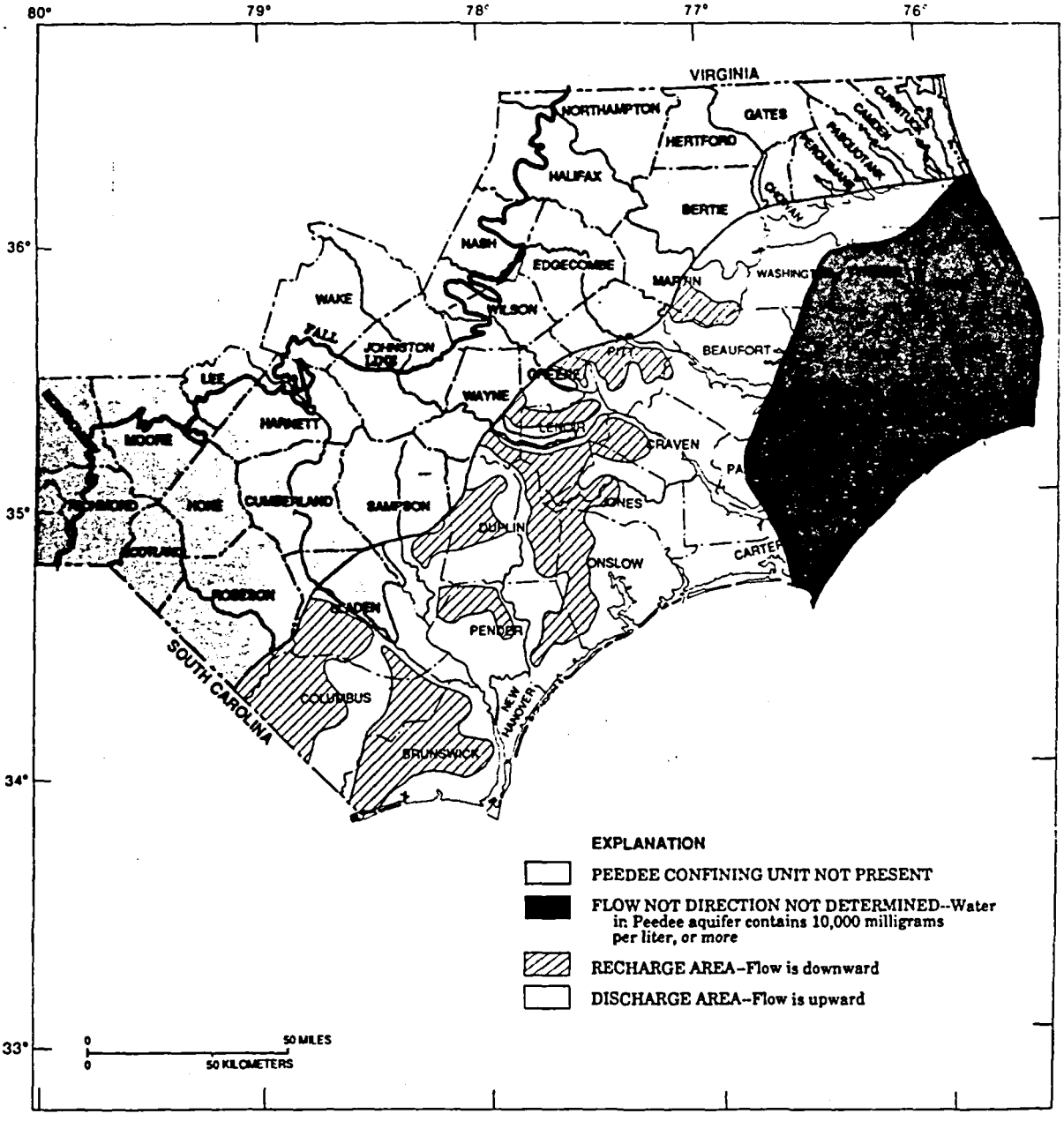


Figure 105.--Net vertical flow of water through the Peedee confining unit (CU5) simulated for predevelopment (1900) conditions.

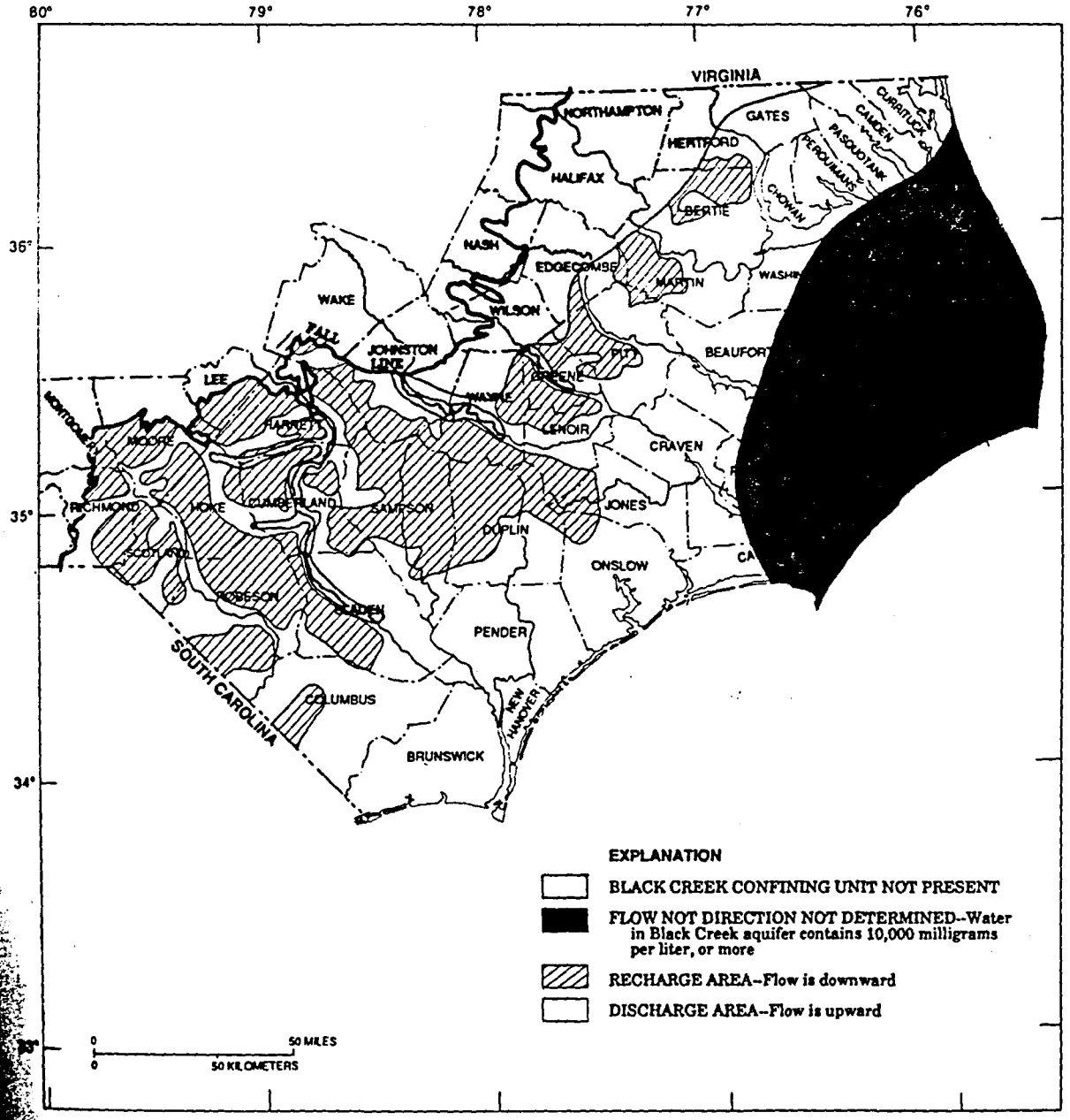


Figure 106.--Net vertical flow of water through the Black Creek confining unit (CU4) simulated for predevelopment (1900) conditions.

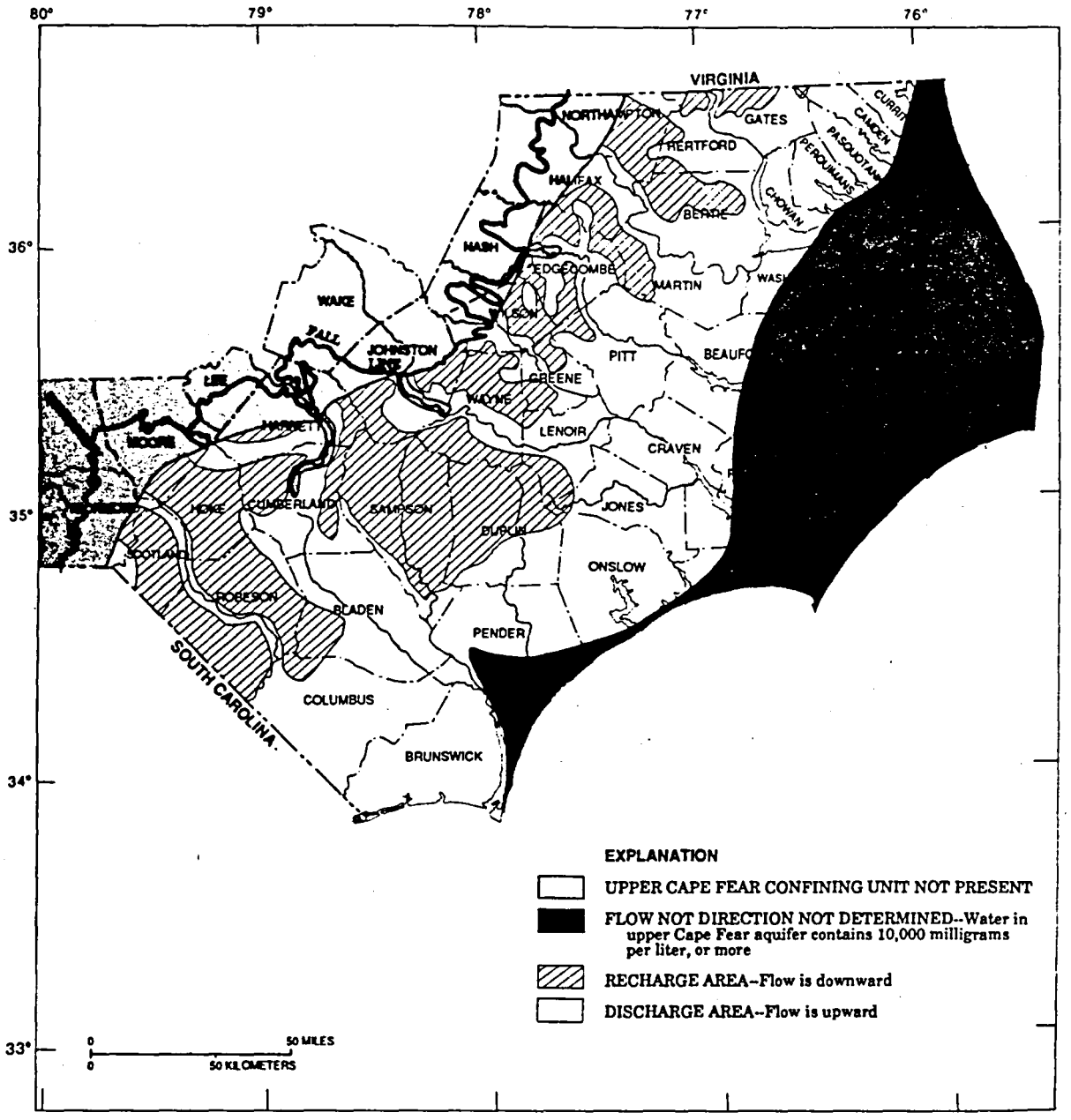


Figure 107.--Net vertical flow of water through the upper Cape Fear confining unit (CU3) simulated for predevelopment (1900) conditions.

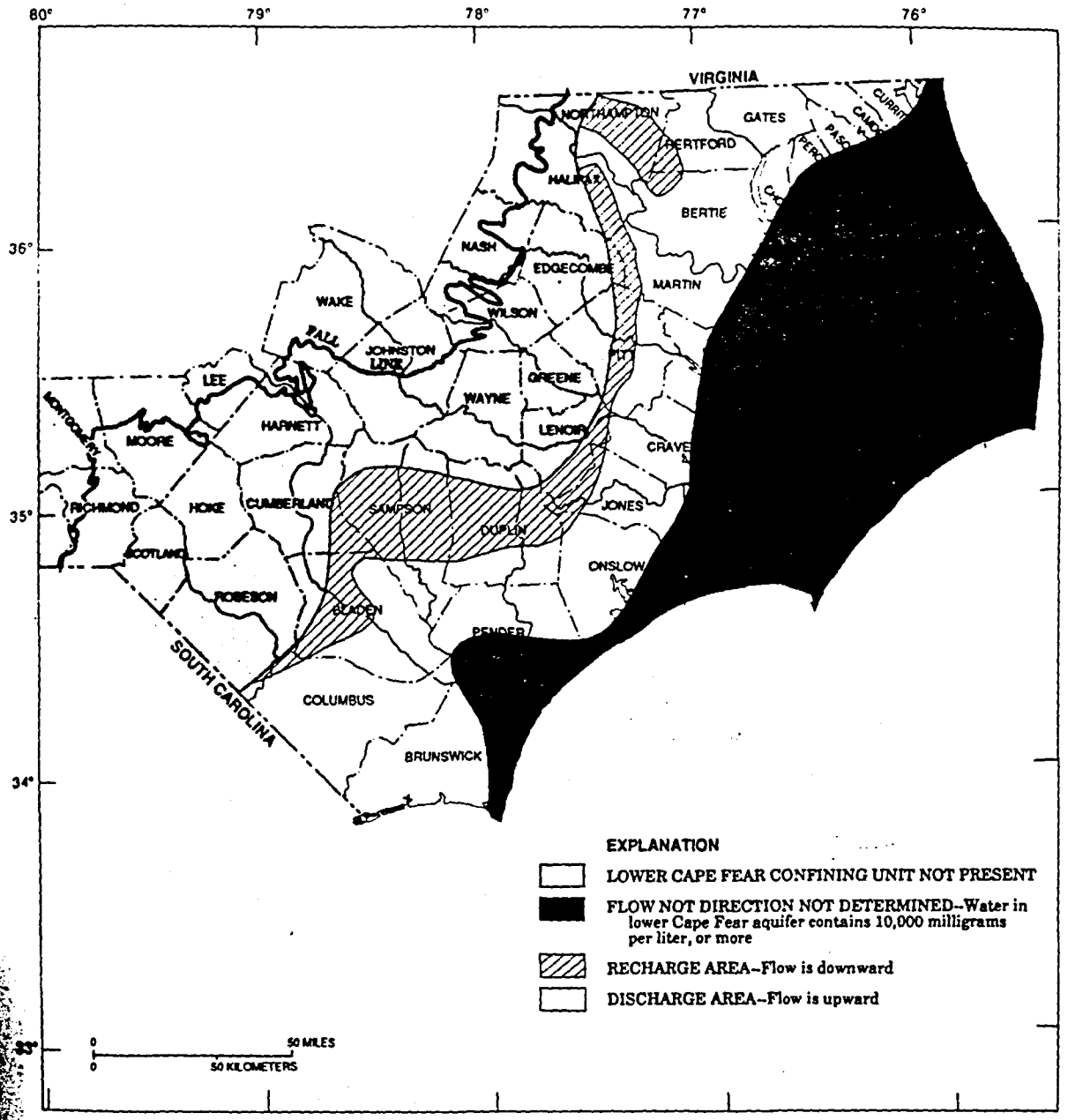


Figure 108.--Net vertical flow of water through the lower Cape Fear confining unit (CU2) simulated for predevelopment (1900) conditions.

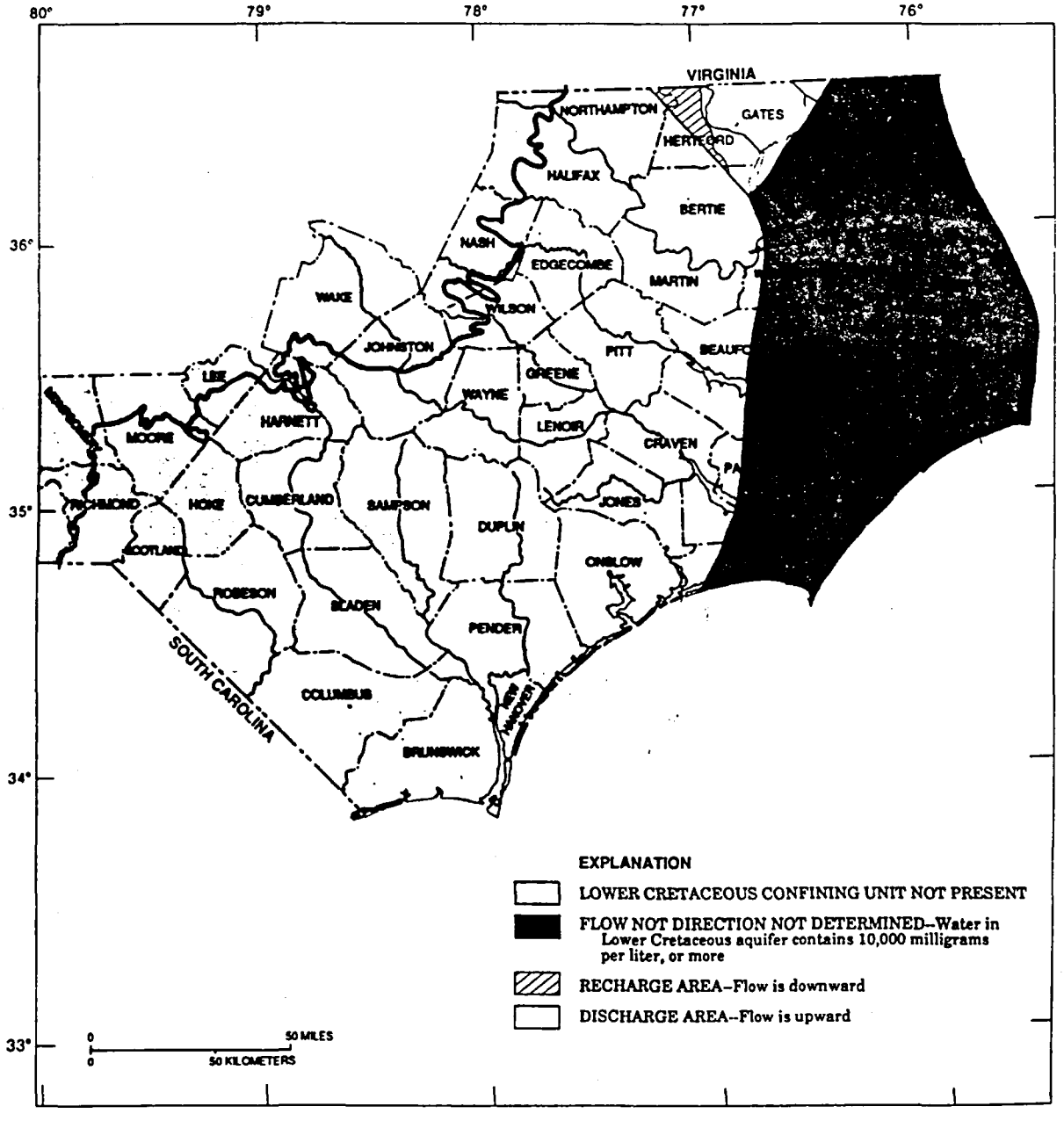


Figure 109.--Net vertical flow of water through the Lower Cretaceous confining unit (CU1) simulated for predevelopment (1900) conditions.

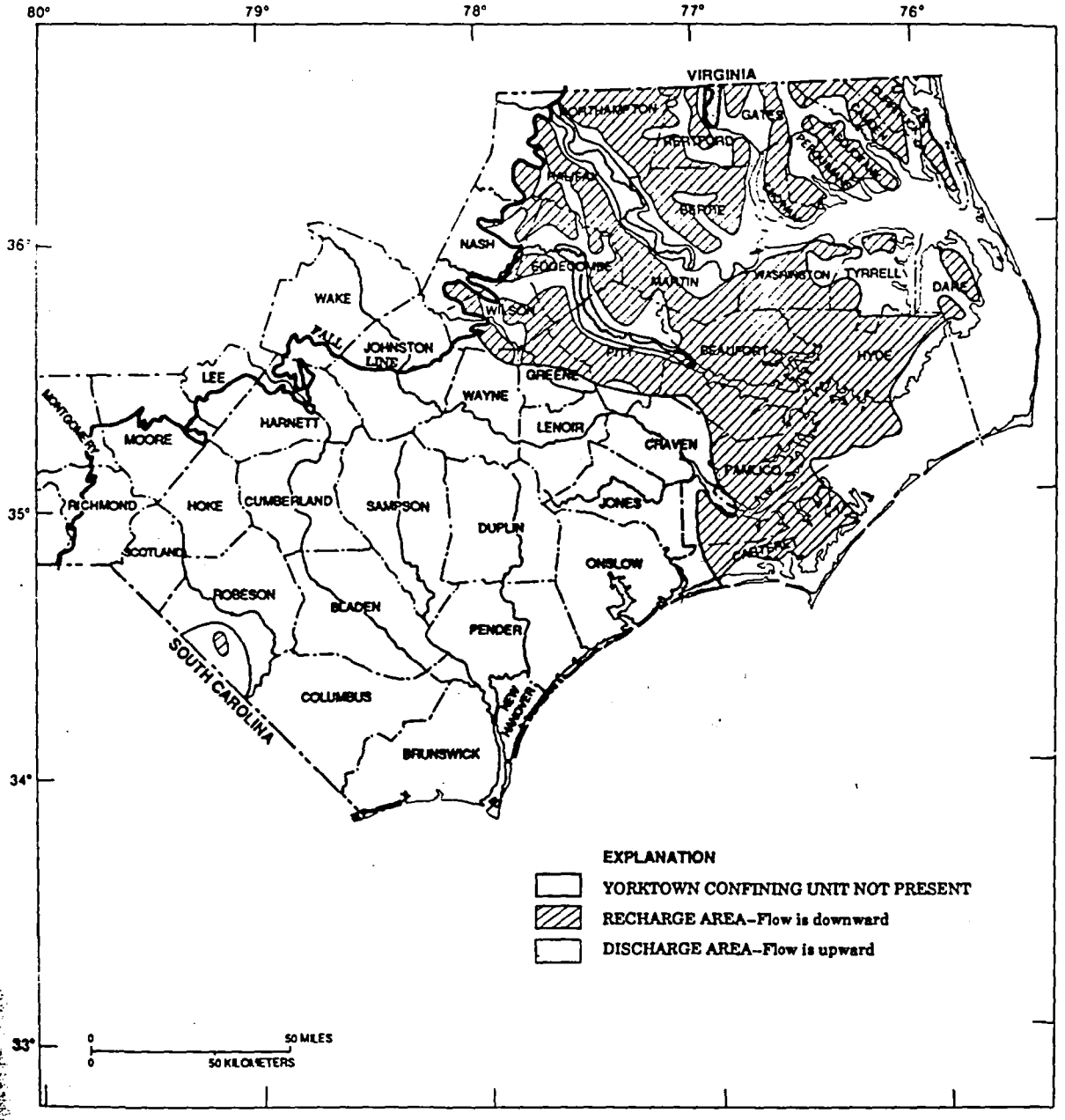


Figure 110.--Net vertical flow of water through the Yorktown confining unit (CU9) simulated for 1980 conditions.

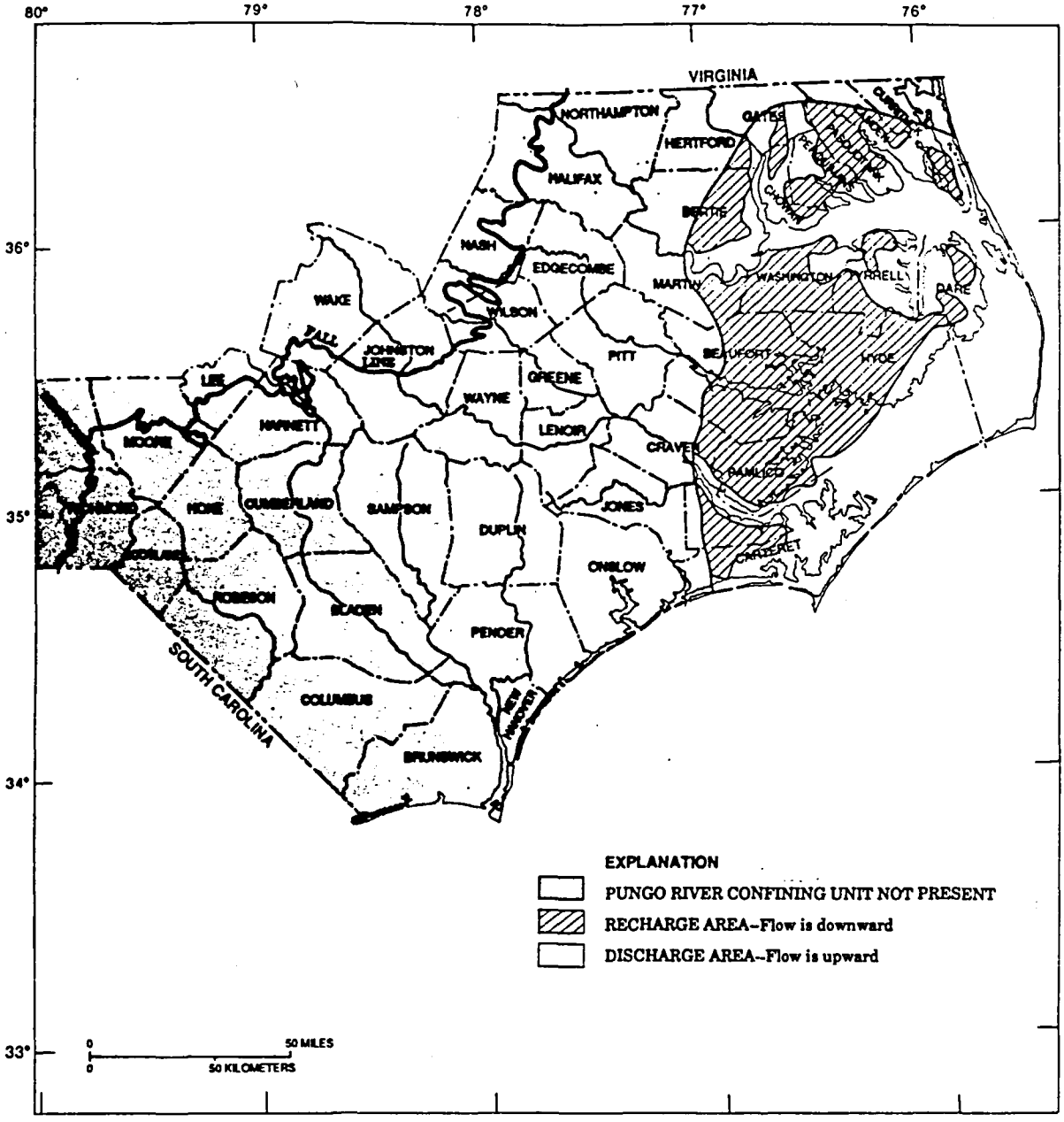


Figure 111.--Net vertical flow of water through the Pungo River confining unit (CU8) simulated for 1980 conditions.

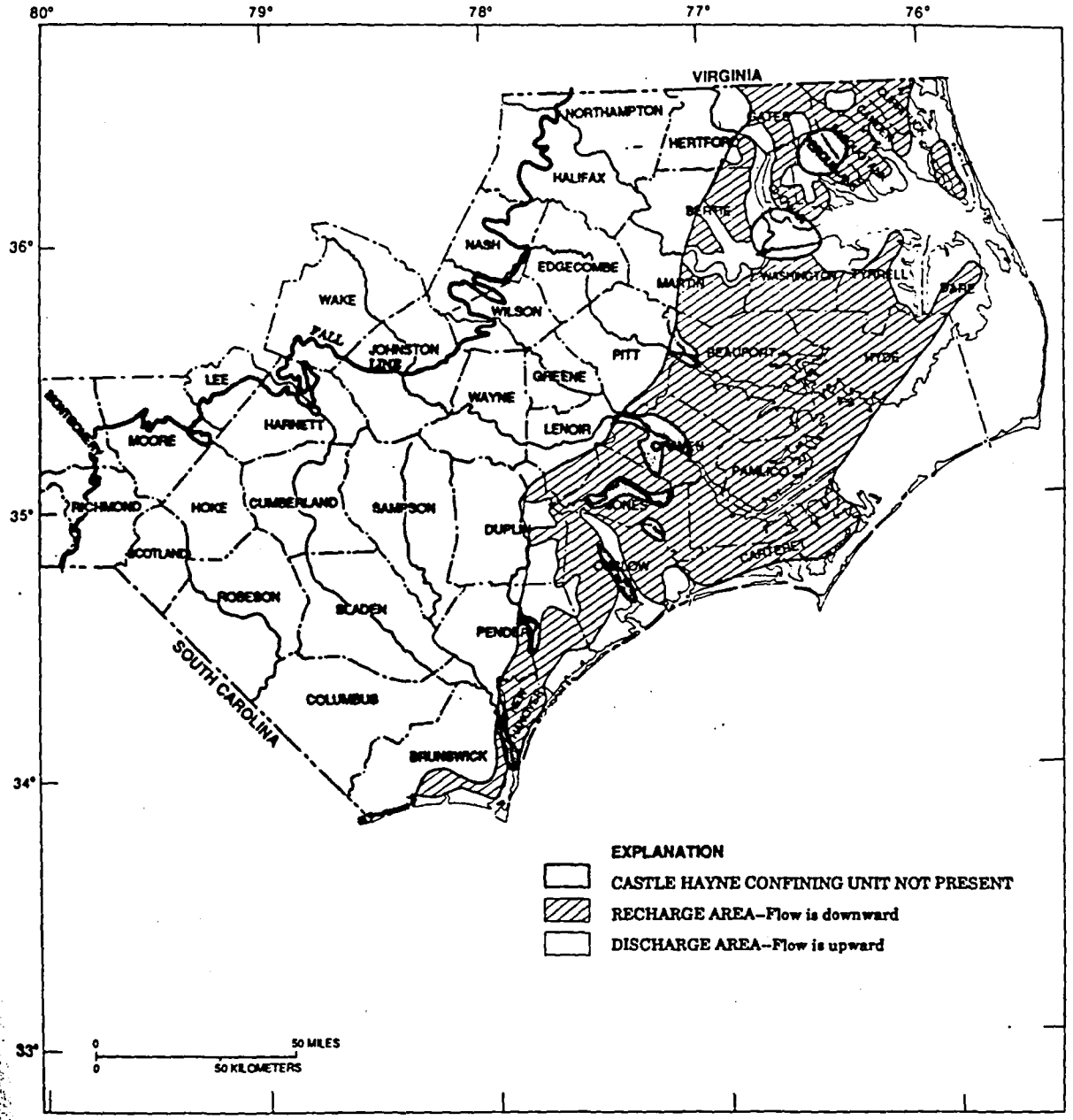


Figure 112.--Net vertical flow of water through the Castle Hayne confining unit (CU7) simulated for 1980 conditions.

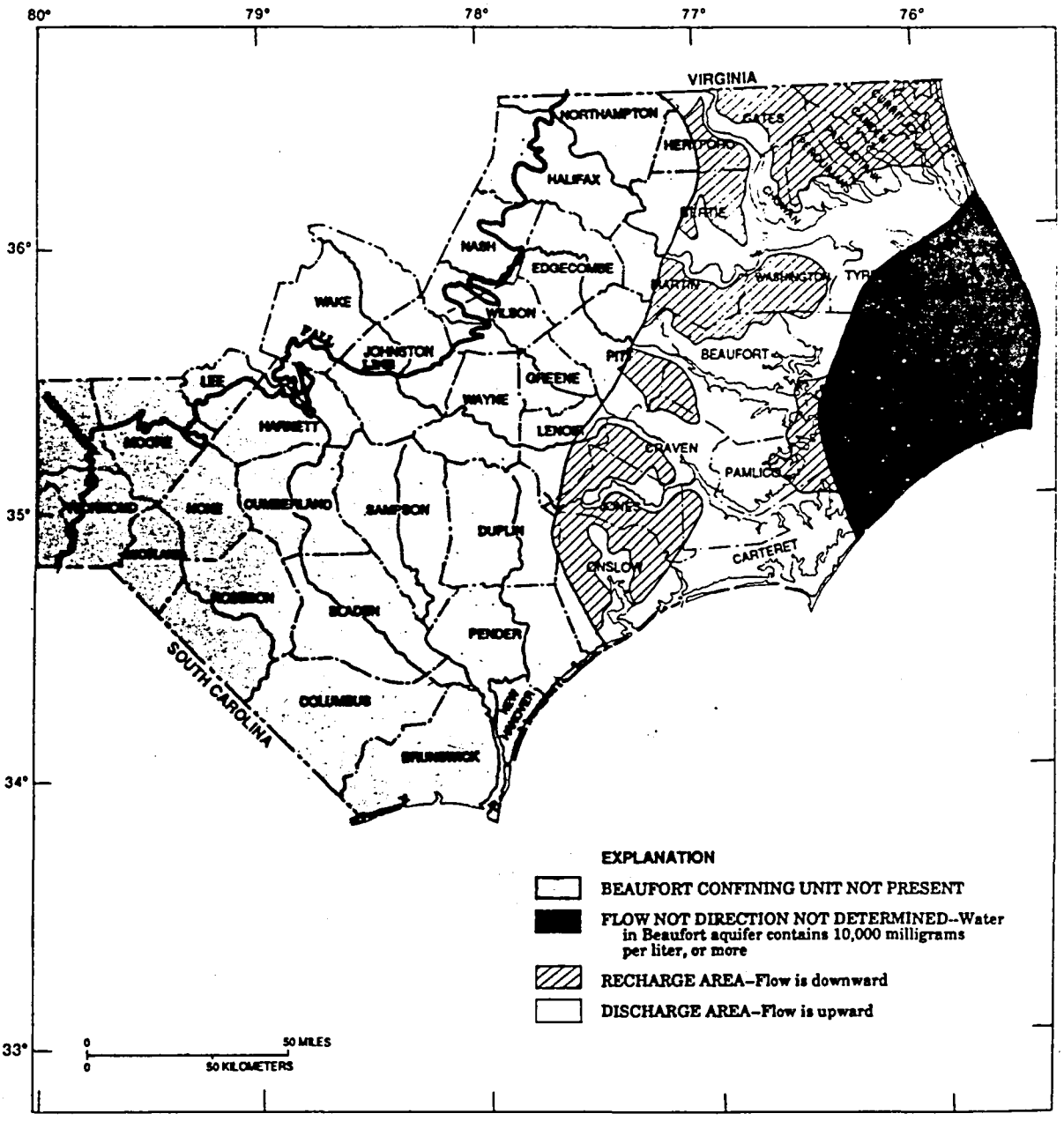


Figure 113.--Net vertical flow of water through the Beaufort confining unit (CU6) simulated for 1980 conditions.

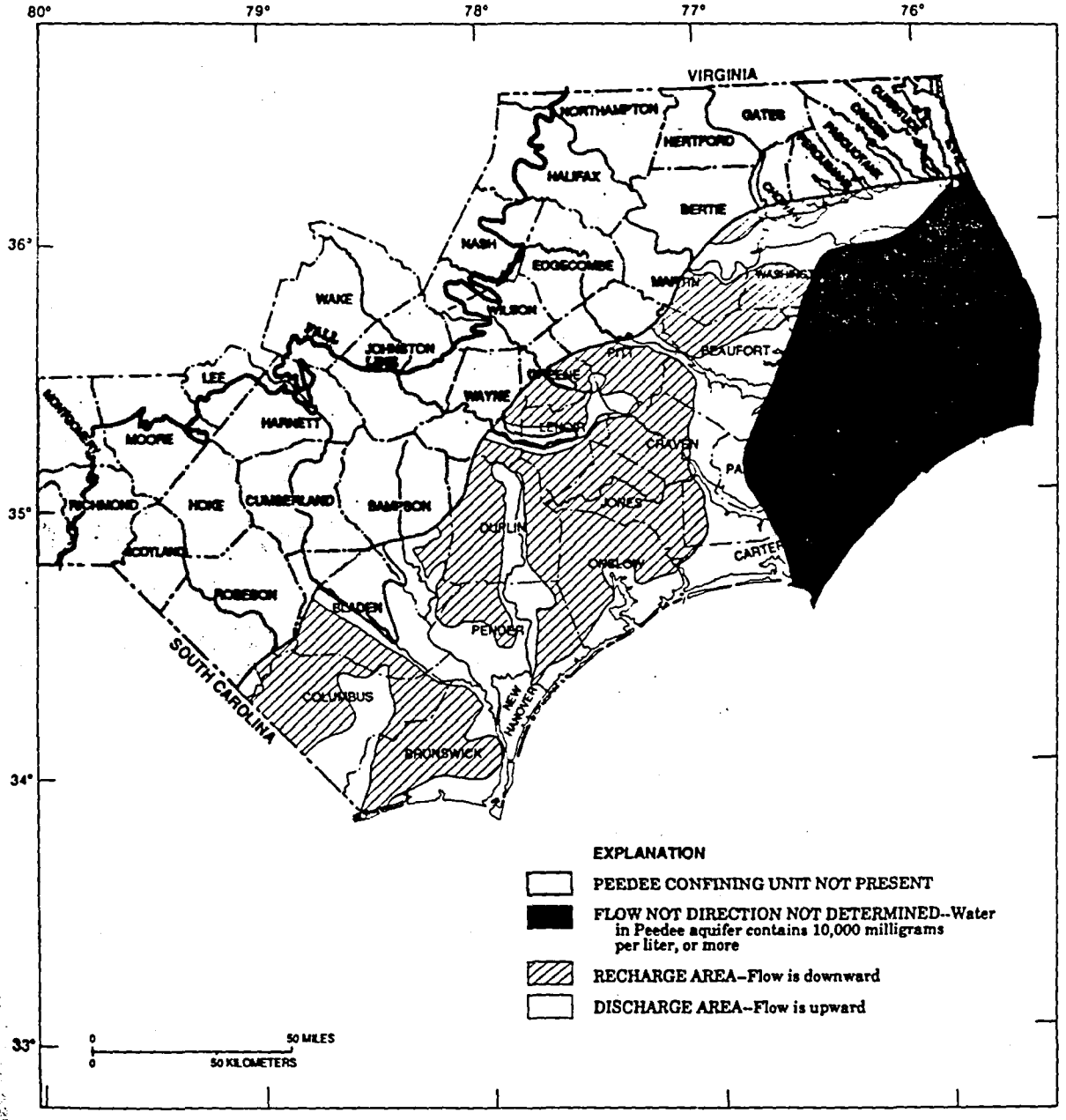


Figure 114.--Net vertical flow of water through the Peedee confining unit (CU5) simulated for 1980 conditions.

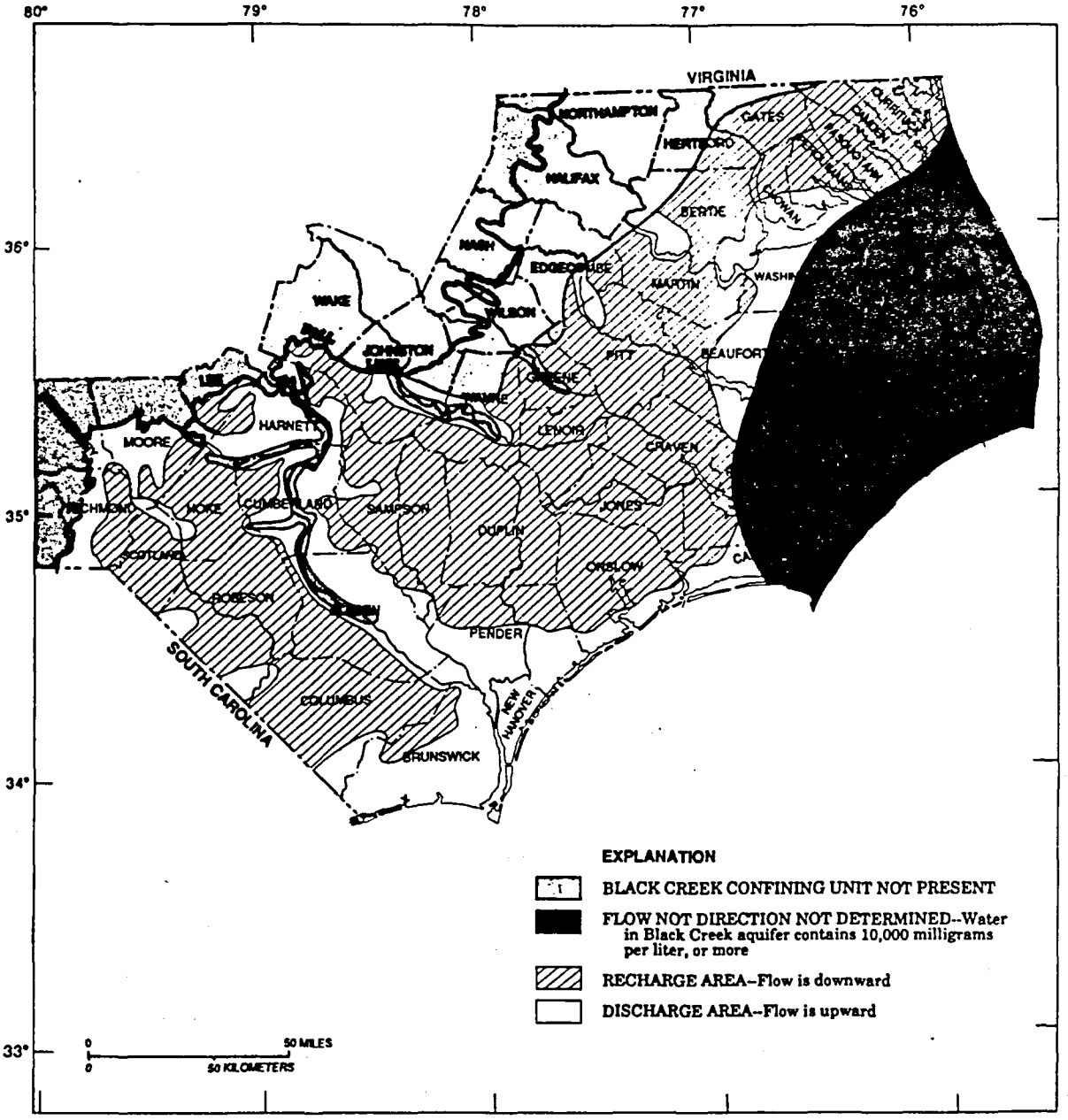


Figure 115.--Net vertical flow of water through the Black Creek confining unit (CU4) simulated for 1980 conditions.

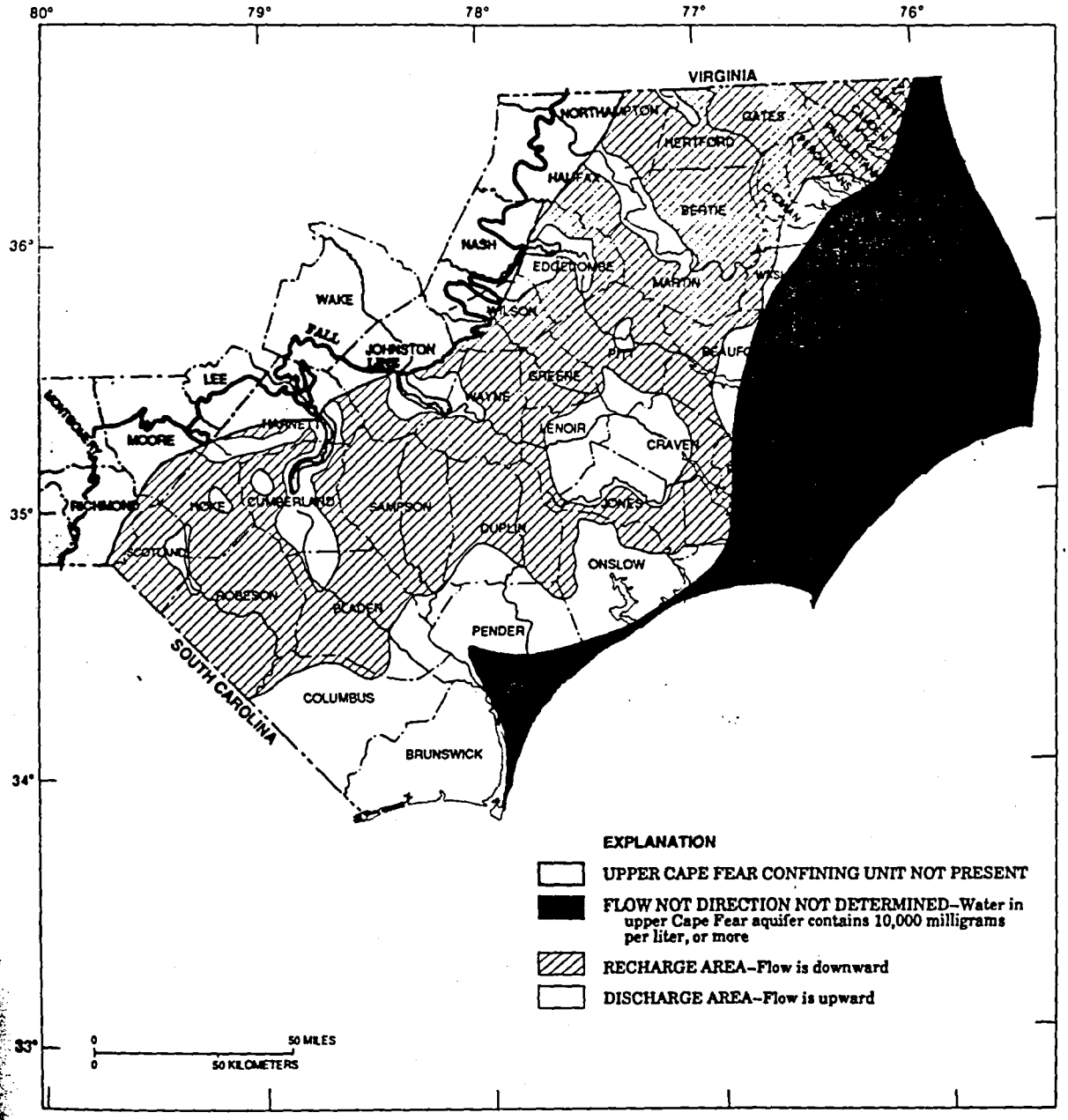


Figure 116.--Net vertical flow of water through the upper Cape Fear confining unit (CU3) simulated for 1980 conditions.

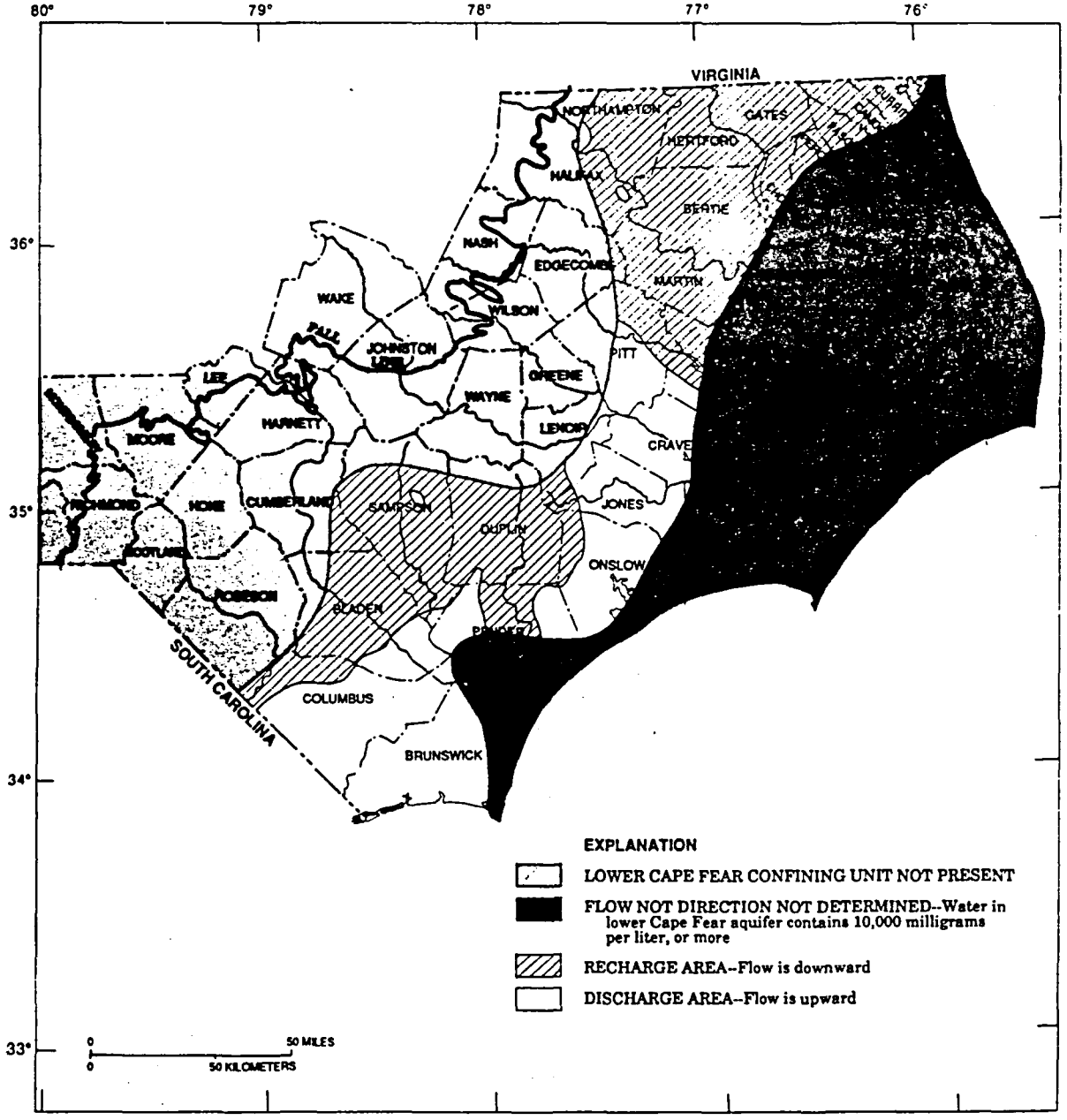


Figure 117.--Net vertical flow of water through the lower Cape Fear confining unit (CU2) simulated for 1980 conditions.

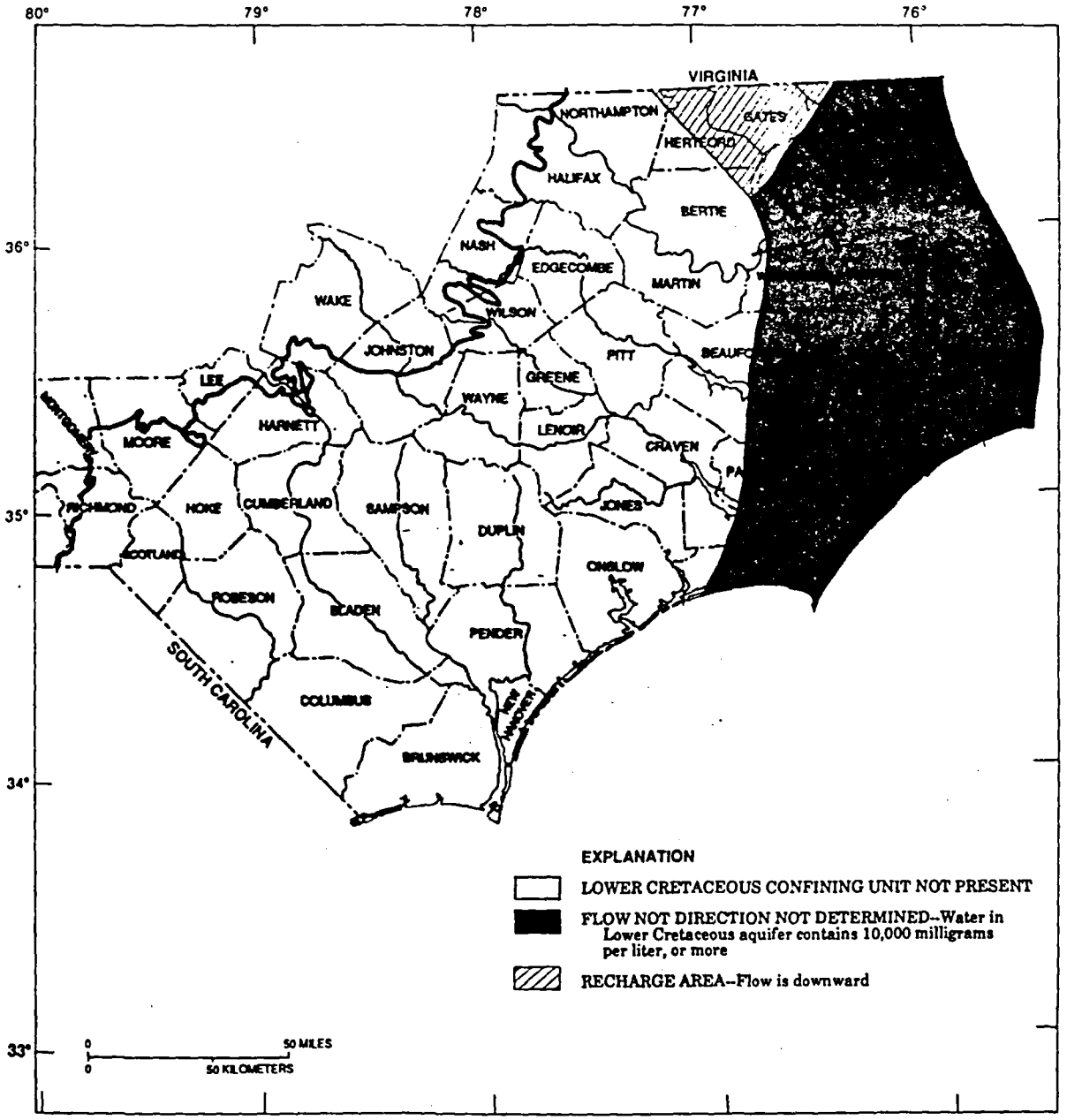


Figure 118.--Net vertical flow of water through the Lower Cretaceous confining unit (CU1) simulated for 1980 conditions.

In the Beaufort County area, vertical flow under prepumping conditions was generally upward, this being a discharge area for most of the North Carolina Coastal Plain aquifers present there. After large-scale pumping began in 1965 in the Castle Hayne aquifer (A7), vertical flow was toward the Castle Hayne aquifer; that is, upward vertical flow across confining units CU6 and CU5 was greater than before, and vertical flow through the Yorktown (CU9) through Castle Hayne (CU7) confining units reversed direction from upward to downward in the vicinity of the large-scale pumping areas.

SUMMARY AND CONCLUSIONS

A three-dimensional finite-difference digital flow model was developed to simulate ground-water flow in the Coastal Plain aquifer system of North Carolina, covering an area of 25,000 mi^2. The 10-layer model was developed from a hydrogeologic framework comprising an alternating sequence of aquifers and confining units that dip and thicken in the seaward direction. The model code used was a three-dimensional finite-difference ground-water flow model, and the modeled area was divided into a rectangular grid for each of the 10 layers with variable spacing representing areas ranging from 12.25 mi^2 to 56.25 mi^2. The grid and boundary conditions of the mathematical-numerical model were designed to be compatible with a regional model of the entire North Atlantic Coastal Plain.

Western and eastern boundaries for each of the model layers were treated as no-flow boundaries. The eastern boundaries were assumed to be along lines of equal concentrations of 10,000 mg/L of dissolved chloride. Boundaries at the State lines, Virginia to the north and South Carolina to the south, were specified flux boundaries with the fluxes provided by the regional model. The upper boundary of each confined aquifer was the bottom of its associated confining unit, which was treated as a head-dependent flux boundary.

Viewing the model as a whole, the upper boundary was the layer representing streams (a constant-head boundary), and the lower boundary was either bedrock or a saltwater-bearing aquifer (no-flow boundary). The treatment of the line representing the 10,000 mg/L chloride concentration as a no-flow boundary was valid in areas not affected by pumping, but was not

valid where effects of pumping extend to the boundary, as in parts of the Beaufort (A6), Black Creek (A4), upper Cape Fear (A3), lower Cape Fear (A2), and Lower Cretaceous (A1) aquifers. In these areas, the model will tend to predict greater drawdown than would actually occur.

Model input consisted of transmissivity and storage coefficients of the aquifers, confining-unit and streambed leakance, ground-water recharge, water-table and stream-surface altitudes, boundary-flux rates, and pumpage. For transient simulations, 10 pumping periods starting in 1900 and running through 1980 were used. Pumping periods ranged in length from 21 years (first pumping period) to 3 years (last pumping period).

A number of calibration simulations were made for the purpose of testing how well the model was able to reproduce measured water levels and as an aid to indicate where adjustments to model parameters were needed. The primary parameters adjusted were leakance of the confining units and, to a lesser extent, transmissivity of the aquifers.

In the calibration procedures about 240 computed hydrographs were compared with observed hydrographs. Also, computed potentiometric surfaces at various times were checked with actual water-level data. Adjustments to model parameters were made after careful consideration of whether the adjustments could be justified based on data on the hydrogeologic and ground-water flow systems. The largest changes were in estimates of leakance of confining units and were considered reasonable because the initial values of this parameter were known with less certainty than any other parameters.

For the calibrated model, the maximum transmissivity was about 200,000 ft^2/day in a part of the Castle Hayne aquifer (A7). The smallest vertical hydraulic conductivity of a confining unit for the calibrated model was about 4.1×10^{-6} ft/day in a part of the lower Cape Fear confining unit. Simulations indicate that a barrier to flow exists in the vicinity of a landward reentrant of water containing 10,000 mg/L of dissolved chloride in the upper and lower Cape Fear aquifers (A3 and A2) over the Cape Fear Arch in the Wilmington area. The barrier is probably the cause of the high hydraulic heads in these two aquifers southwest of the Arch in southeast

North Carolina and northeast South Carolina. The nature of the barrier needs further research but is likely due to either diminished hydraulic conductivity in the area or to the presence of salty water, or both.

The relatively large block size made it difficult to accurately simulate the configuration of the water table in the Sand Hills area. Thus, the model is probably less accurate in this area than in any other area in the North Carolina Coastal Plain.

Sensitivity analysis indicated that the model is especially sensitive to changes in transmissivity in areas where pumping occurs, but regionally the model is more uniformly sensitive to leakance through the confining units. Sensitivity of the model to changes in storage coefficient of the confined aquifers is slight and, as with transmissivity, is greatest near the pumping centers.

Under predevelopment (1900) conditions, average recharge from precipitation to the surficial aquifer varied areally from about 12 in/yr in areas with clay soils to 20 in/yr in areas with sandy soils. Most of this moved directly to streams with only about 1 in/yr moving downward into the confined aquifer system. Generally, recharge to the confined aquifer system took place mostly in updip interstream areas, and discharge occurred in streams and stream valleys and in downdip coastal areas. Hydrologic analysis of the aquifer system based on simulations indicates that the overall water budget has changed little from predevelopment conditions in 1900 to development conditions in 1980. Pumpage from large users increased from zero to 302 ft^3/s during that period, which amounts to about 1.2 percent of the recharge to the ground-water system of 25,703 ft^3/s. Simulation results indicate that water lost to the aquifer system through pumping is largely offset by reductions in base flow of streams and, to a lesser extent, by reductions in aquifer storage. By 1980, contribution from aquifer storage was about 14 ft^3/s, or about 4.8 percent of pumpage.

Although the effect of pumping on the overall water budget is relatively small, water levels in the North Carolina Coastal Plain aquifer system have declined dramatically in parts of some aquifers since 1900 (more than 135 ft in some locations) due to pumping stresses. The three principal

areas of long-term water-level decline are in the Lower Cretaceous (A1) and lower Cape Fear (A2) aquifers in northeast North Carolina in response to withdrawals at Franklin, Virginia; in the lower Cape Fear (A2), upper Cape Fear (A3), and Black Creek (A4) aquifers in the central North Carolina Coastal Plain where pumping occurs at several sites; and in the Beaufort (A6) and Castle Hayne (A7) aquifers in Beaufort County where there are large withdrawals for open-pit phosphate mining and chemical manufacturing.

Since 1900, water levels have declined less than 10 ft in the surficial (A10) and Yorktown (A9) aquifers; this is also true of the updip parts of most of the other aquifers where major withdrawals were not occurring in 1980. Simulations to the year 2000 with a 3-percent annual increase in withdrawals at 1980 pumping locations gave virtually the same results as the 1980 simulations of the same two shallow aquifers and updip parts of the other aquifers. The year 2000 simulations indicated significant local water-level declines in lower confined aquifers but, on a cell basis, not below the tops of the aquifers.

Directions of vertical flow through confining units have been altered in many areas since 1900. In 1900, vertical ground-water flow through confining units was generally downward in interstream areas and upward in major stream valleys and in coastal areas. Ground-water pumpage substantially altered that pattern in several areas. The most widespread change caused ground water to move downward into pumped aquifers in areas where it had moved upward in predevelopment times. By 1980, areas of downward movement commonly occurred in major stream valleys. Areas of downward movement also extended farther coastward in 1980 than in 1900 in confining units overlying extensively developed aquifers.

SELECTED REFERENCES

Aucott, W.R., and Speiran, G.K., 1985, Ground-water flow in the Coastal Plain aquifers of South Carolina: Ground Water, v. 23, no. 6, p. 736-745.

Aucott, W.R., Davis, M.E., and Speiran, G.K., 1987, Geohydrologic framework of the Coastal Plain aquifers of South Carolina: U.S. Geological Survey Water-Resources Investigations Report 85-4271.

Beck, M.B., and van Straten, Gerrit, eds., 1983, Uncertainty and forecasting of water quality: New York, Springer-Verlag, 386 p.

Blankenship, R.R., 1965, Reconnaissance of ground-water resources of the Southport-Elizabethtown area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 6, 47 p.

Brown, D.L., and Cosner, O.J., 1974, Ground-water conditions in the Franklin area, southeastern Virginia: U.S. Geological Survey Hydrologic Investigations Atlas, HA-538, 3 sheets.

Brown, P.M., 1958, Well logs from the Coastal Plain of North Carolina: North Carolina Department of Conservation and Development Bulletin 72, 68 p.

_____1959, Geology and ground-water resources in the Greenville area, North Carolina: North Carolina Department of Conservation and Development Bulletin 73, 87 p.

Brown, P.M., Miller, J.A., and Swain, F.M., 1972, Structural and stratigraphic framework and spatial distribution of the permeability of the Atlantic Coastal Plain, New York to North Carolina: U.S. Geological Survey Professional Paper 796, 79 p.

Clark, W.B., Miller, B.L., Stephenson, L.W., Johnson, B.L., and Parker, H. N., 1912, The Coastal Plain of North Carolina: North Carolina Geological and Economic Survey Bulletin 3, 372 p.

Coble, R.W., Giese, G.L., and Winner, M.D., Jr., 1987, Application of regional aquifer-system analysis study results to ground-water management in North Carolina, *in* Vecchioli, John, and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph Series No. 9, p. 39-49.

Cosner, O.J., 1975, A predictive computer model of the Lower Cretaceous aquifer, Franklin area, southeastern Virginia: U.S. Geological Survey Water-Resources Investigations 51-74, 62 p.

Daniel, J.F., 1976, Estimating evapotranspiration from streamflow records: Water Resources Research, June 1976, p. 360-364.

DeWiest, R.J.M., Sayre, A.N., and Jacob, C.E., 1967, Evaluation of potential impact of phosphate mining on ground-water resources of eastern North Carolina: Board of Consultants Report to North Carolina Department of Water Resources, 167 p.

Eder, B.K., Davis, J.M., and Robinson, P.J., 1983, Variations in monthly precipitation over North Carolina: University of North Carolina Water Resources Research Institute Report No. 83-185, 50 p.

Emsellem, Y., and deMarsily, G., 1971, An automatic solution for the inverse problem: Water Resources Research, v. 7, n. 5, p. 1264-1283.

Fenneman, N.M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Company, Inc., 714 p.

Floyd, E.O., and Peace, R.R., 1974, An appraisal of the ground-water resources of the upper Cape Fear River basin, North Carolina: North Carolina Department of Water and Air Resources Ground-Water Bulletin 20, 17 p.

Franke, O.L., Reilly, T.E., and Bennett, G.D., 1984, Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems--an introduction: U.S. Geological Survey Open-File Report 84-458, 26 p.

Giese, G.L., Wilder, H.B., and Parker, G.G., Jr., 1985, Hydrology of major estuaries and sounds of North Carolina: U.S. Geological Survey Water-Supply Paper 2221, 108 p.

Harris, W.H., and Wilder, H.B., 1966, Geology and ground-water resources of the Hertford-Elizabeth City area, North Carolina: North Carolina Department of Water Resources Ground-Water Bulletin 10, 89 p.

Harsh, J.F., and Laczniak, R.J., 1990, Conceptualization and analysis of ground-water flow in the Coastal Plain aquifers of Virginia and parts of Maryland and North Carolina: U.S. Geological Survey Professional Paper 1404-F, 100 p..

Heath, R.C., 1980, Basic elements of ground-water hydrology with reference to conditions in North Carolina: U.S. Geological Survey Water Resources Investigations Open-File Report 80-44, 86 p.

Hitchon, B., 1969, Fluid flow in the western Canada sedimentary basin 1. Effect of topography: Water Resources Research, v. 5, no. 1, p. 186-195.

Kimrey, J.O., 1965, Description of the Pungo River Formation in Beaufort County, North Carolina: North Carolina Department of Conservation and Development, Division of Mineral Resources Bulletin 79, 131 p.

Layne-Western Company, Inc., 1983, Virginia/North Carolina analog model study: Kansas City, Kansas, v. 1, 131 p.

Leahy, P.P., 1982, A three-dimensional ground-water flow model modified to reduce computer memory requirements and better simulate confining bed and aquifer pinchouts: U.S. Geological Survey Water Resources Investigations 82-4023, 59 p.

Leahy, P.P., and Martin, Mary, Geohydrology and simulation of ground-water flow in the northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404-K, (in press).

LeGrand, H.E., 1955, Brackish water and its structural implications in the Great Carolina Ridge, North Carolina: American Association of Petroleum Geologists Bulletin, v. 39, no. 10, p. 2020-2037.

_____1960, Geology and ground-water resources of the Wilmington-New Bern area: North Carolina Department of Water Resources Ground-Water Bulletin no. 1, 80 p.

_____1961, Summary of geology of Atlantic Coastal Plain: The Bulletin of the American Association of Petroleum Geologists, v. 45, no. 9, p. 1557-1571.

_____1964, Hydrogeologic framework of the Gulf and Atlantic Coastal Plain: Southeastern Geology, v. 5, no. 4, p. 177-194.

_____1976, Hydrologic implications of the 1886 Charleston earthquake: Proceedings of the Southeastern meeting of the Geological Society of America, v. 8, no. 2, p. 216.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Martin, Mary, 1990, Ground-water flow in the New Jersey Coastal Plain: U.S. Geological Survey Open-File Report 87-528 (pending publication as Professional Paper 1404-H), 182 p.

Meisler, Harold, 1989, The occurrence and geochemistry of salty ground water in the northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 1404-D, 51 p.

_____1986, Northern Atlantic Coastal Plain regional aquifer-system study, *in* Sun, R.J., ed., Regional aquifer-system analysis program of the U.S. Geological Survey, summary of projects, 1978-84: U.S. Geological Survey Circular 1002, 264 p.

Meng, A.A., III, and Harsh, J.F., 1984, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Open-File Report 84-278, 78 p.

Morris, D.A., and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60: U.S. Geological Survey Water-Supply Paper 1839-D, 42 p.

Mundorff, M.J., 1946, Ground-water in the Halifax area, North Carolina: North Carolina Department of Conservation and Development Bulletin 51, 76 p.

Narkunas, James, 1980, Groundwater evaluation in the central Coastal Plain of North Carolina: North Carolina Department of Natural Resources and Community Development, 119 p.

Nelson, P.F., 1964, Geology and ground-water resources of the Swanquarter area: North Carolina Department of Water Resources Ground-Water Bulletin 4, 79 p.

_____1976, Interim report on ground-water conditions in capacity-use area no. 1, central Coastal Plain, North Carolina, 1974-75: North Carolina Department of Natural and Economic Resources Report of Investigations no. 13, 55 p.

Nelson, P.F., and Barksdale, R.G., 1965, Interim report on the ground-water resources of the Kinston area, North Carolina: North Carolina Department of Water Resources Ground-Water Circular 10, 31 p.

North Carolina Department of Natural Resources and Community Development, 1983, Use of water in North Carolina--self supplied industrial use for 1981: Raleigh, Office of Water Resources publication, 42 p.

North Carolina Department of Natural Resources and Community Development and U.S. Water Resources Council, 1983, Survey of agricultural irrigation 1982 lower Cape Fear River basin: Raleigh, N.C., 31 p.

Peek, H.M., 1977, Interim report on ground-water conditions in northeastern North Carolina: North Carolina Department of Natural Resources and Community Development Report of Investigations no. 15, 29 p.

Peek, H.M., and Register, L.A., 1975, A preliminary report on anomalous pressure in deep artesian aquifers in southeastern North Carolina: North Carolina Department of Natural and Economic Resources Report of Investigations no. 10, 20 p.

Robison, T.M., 1977, Public water supplies of North Carolina, part 4, northern Coastal Plain: North Carolina Department of Natural and Economic Resources, 218 p.

Robison, T.M., and Mann, L.T., Jr., 1977, Public water supplies of North Carolina, part 5, southern Coastal Plain: North Carolina Department of Natural Resources and Community Development, 333 p.

Rorabaugh, M.I., 1964, Estimating changes in bank storage and ground-water contribution to streamflow: International Association of Scientific Hydrology Publication 63, p. 432-441.

Schipf, R.G., 1961, Geology and ground-water resources of the Fayetteville area: North Carolina Department of Water Resources Ground-Water Bulletin 3, 99 p.

Sherwani, J.K., 1973, Computer simulation of ground-water aquifers of the Coastal Plain of North Carolina: University of North Carolina Water Resources Research Institute Report No. 75, 126 p.

Steinhorst, R.K., Hurt, H.W., Innis, G.S., and Haydock, K.P., 1978, Sensitivity analysis of the ELM Model, in Innis, G.S. (ed.), Grassland simulation model: New York, Springer-Verlag, p. 231-256.

Stephenson, L.W., and Rathbun, M.J., 1923, The Cretaceous Formations of North Carolina: North Carolina Geological and Economic Survey, v. 5, pt. 1, 604 p.

Stuckey, J.L., 1965, North Carolina: Its geology and mineral resources: Raleigh, North Carolina Department of Conservation and Development, 550 p.

Tant, P.L., Byrd, H.J., and Horton, R.E., 1974, General soil map of North Carolina: U.S. Soil Conservation Service 1:1,000,000 scale map.

Tomovic, R., 1962, Sensitivity analysis of dynamic systems: New York, McGraw-Hill, 142 p.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 48 p.

Trescott, P.C., and Larson, S.P., 1976, Supplement to Open-File Report 75-438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p.

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 7, chap. C1, 116 p.

Wilder, H.B., and Simmons, C.E., 1982, Program for evaluating stream quality in North Carolina: U.S. Geological Survey Water-Supply Paper 2185-A, 15 p.

Wilder, H.B., Robison, T.M., and Lindskov, K.L., 1978, Water resources of northeast North Carolina: U.S. Geological Survey Water-Resources Investigations 77-81, 113 p.

Winner, M.D., Jr., and Coble, R.W., 1989, Hydrogeologic framework of the North Carolina Coastal Plain aquifer system: U.S. Geological Survey Open-File Report 87-690, 155 p.

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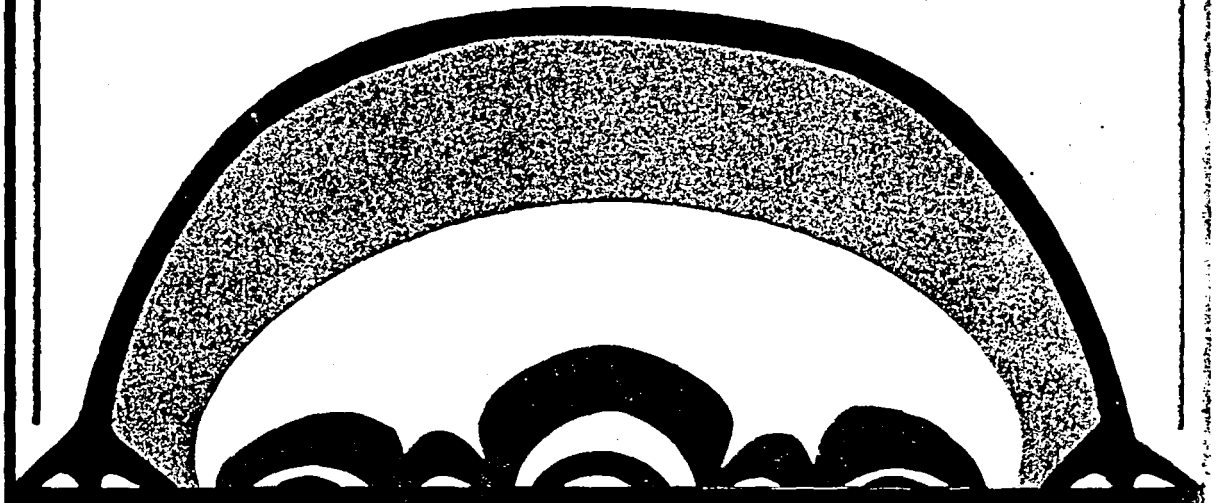
Reference 21

GROUNDWATER



R. Allan Freeze/John A. Cherry

Table 2.2 Range of Values of Hydraulic Conductivity and Permeability

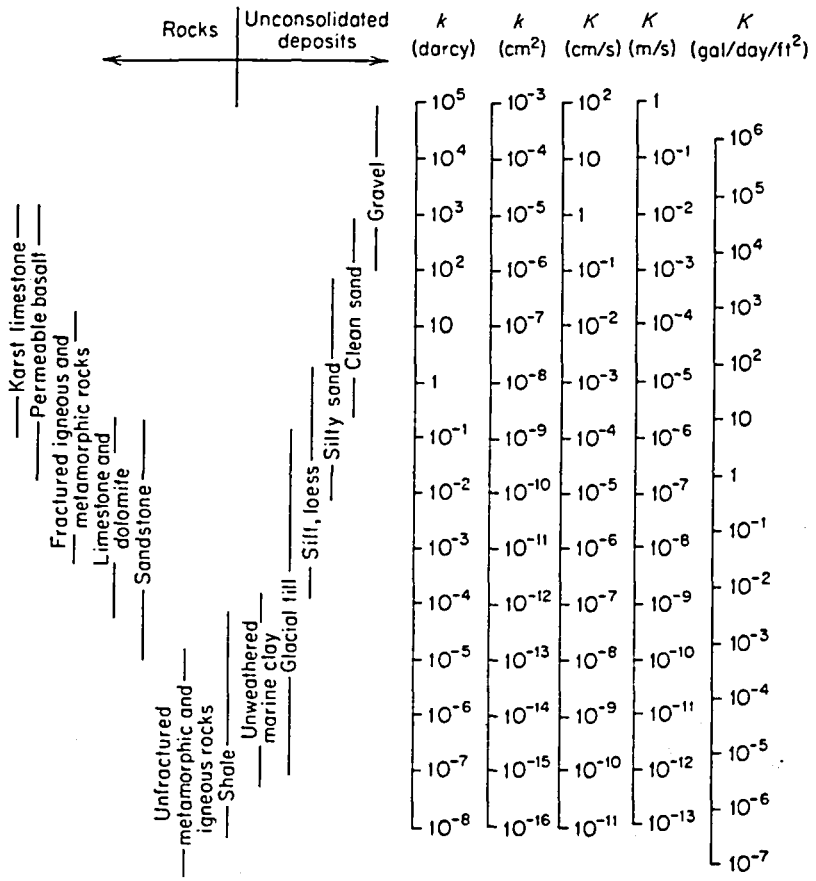


Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm²	ft²	darcy	m/s	ft/s	U.S. gal/day/ft²
cm²	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft²	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft²	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft², multiply k in cm² by 1.08×10^{-3}.